NBS TECHNICAL NOTE 1089

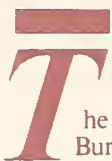**U.S. DEPARTMENT OF COMMERCE** / National Bureau of Standards

Site Attenuation

R. G. FitzGerrell

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Site attenuation is a measure of performance of an open test site used at frequencies below about 1 GHz for antenna calibration and equipment emission and susceptibility testing. These sites typically consist of a large, obstruction-free ground plane and the hemisphere above it. Site attenuation of an ideal site is calculated and compared to data measured using the 30 m by 60 m NBS ground screen.

Key words: antenna measurements; dipole antennas; site attenuation.

1. Introduction

Site attenuation is a measure of performance of an open test site used to determine the levels of emissions from electromagnetic sources or to calibrate monopole and dipole antennas used for field strength measurements. An ideal site consists of obstruction-free plane ground and the hemisphere above it -- both infinite in extent. Ground constants may range from typical earth values to values for good conductors. Site attenuation measurements are used to compare performance of real sites to the ideal or reference site. Calculations presented here provide a reference for the measurement results obtained from a 30 m by 60 m wire mesh ground screen.

Site attenuation is defined as the minimum relative insertion loss measured between the terminals of two polarization-matched antennas located on the test site when one antenna is moved vertically over a specified height range. The following parameters must also be specified: separation distance between the two antennas, measured horizontally; antenna type and polarization; and impedance of the receiving and transmitting systems attached to the antenna terminals. Calculated and measured site attenuation includes mismatch losses but not balun or cable losses.

2. Calculations

Insertion loss between two thin dipoles in echelon located in free space may be calculated using the mutual impedance between the dipoles [1] and self impedance of the dipoles [2]. The mutual impedance is given as follows:

$$Z_{21} = - \frac{V_{21}}{I_{1b}} .$$

(1)

Assuming the dipoles are identical, the self impedance, Z_i, of each dipole is calculated as described in Appendix I. An arbitrary power level, P_{inc}, is assumed to be delivered to the transmitting dipole and, with Z_i and the transmitter impedance, is used to calculate the base current, I_{1b}. The mutual impedance Z_{21}, is calculated based upon the antenna geometry, and V_{21}, the receiving dipole open circuit voltage, is obtained using (1). The power at the receiving dipole terminals, P_{rec}, is calculated using V_{21}, Z_i and the receiver impedance assuming the receiving dipole current has no effect on the transmitting dipole impedance. That is, any additional mutual impedance effects are ignored. The ratio, P_{inc}/P_{rec}, is the insertion loss between the dipoles.

Insertion loss between two thin dipoles in echelon over perfectly conducting ground may be calculated if they are vertically or horizontally polarized (a restriction occurring only because of the mutual impedance formulations used in this document) and their positions are specified. The test range geometry and multiple mutual impedances required for the calculation are shown in figure 1 for horizontal polarization. The value of I_{1b} is calculated assuming that 1 W is delivered to a transmitting dipole that has an input impedance, Z_{in}, equal to Z_i properly combined with the mutual impedance between it and its image in the perfectly conducting ground. A total mutual impedance consisting of Z_{21} and Z_{23} is calculated and used with I_{1b} to obtain V_{oc}, the open circuit voltage in the receiving dipole. Input impedance of the receiving dipole is calculated and used with V_{oc} to calculate P_{rec}. Again, the impedance of the transmitting dipole is assumed to be unaffected by the current

in the receiving dipole's finite load impedance. This assumption results in an approximation to the true value of P_{rec} and reduces the number of mutual impedance equations required to the four shown in figure 1.

The input impedance for dipole antennas over perfect ground may be written using the notation in figure 1 as follows:

$$Z_{in} = Z_i \pm Z_{13} \quad \text{for the transmitting dipole} \tag{2}$$

and

$$Z_{in}(h) = Z_i \pm Z_{24} \quad \text{for the receiving dipole .} \tag{3}$$

The sign of the mutual impedance terms depend upon polarization, and the fact that the receiving dipole impedance is a function of height, h, is emphasized in the notation. (The transmitting dipole is always at a fixed height.) The mutual impedances are calculated using equations in [1] and Z_i is calculated using equation (4A) given in Appendix I.

The power from the transmitting dipole is given by

$$P_{trans} = P_{inc} (1 - | (Z_{in} - Z_s)/(Z_{in} + Z_s) |) , \tag{4}$$

where P_{inc} is the power delivered to the dipole terminals and Z_s is the transmitter impedance presented to the dipole terminals. The current required in (1) can now be written as

$$I_{1b} = (P_{trans}/\text{Real}(Z_{in}))^{1/2} . \tag{5}$$

The total mutual impedance between the dipole antennas is

$$Z_m(h) = Z_{21}(h) \pm Z_{23}(h) , \tag{6}$$

with the height dependance again emphasized. The receiving dipole open-circuit voltage is obtained as a result of the definition of mutual impedance as

$$V_{oc}(h) = I_{1b} | Z_m(h) | , \tag{7}$$

and the received power is approximately given by

$$P_{rec} (h) = Z_R (V_{oc} (h)/| Z_R + Z_{in} (h) |)^2 , \qquad (8)$$

where Z_R is the receiver impedance presented to the dipole terminals.

Finally, site attenuation is obtained as

$$S_{NBS} = 10 \log_{10} (P_{inc}/P_{rec}(H)) , \qquad (9)$$

where P_{rec} (H) is the maximum value of $P_{rec}(h)$ which occurs at a height H in the range of heights considered. For the calculations presented in this paper, $Z_R = Z_S = 100$ ohms and P_{inc}, an arbitrary value, is set to 1 W.

Insertion loss is the ratio of the power delivered to the transmitting dipole terminals to the power received at the receiving dipole terminals and is a positive quantity. Site attenuation is the minimum insertion loss occurring when the receiving dipole is scanned in height. The height-scan patterns in figure 2 show calculated insertion loss for horizontally polarized (HP) and vertically polarized (VP) dipoles with a 3 m separation distance. The transmitting dipole is 2 m above perfectly conducting ground. Site attenuation is the single minimum value of each pattern. Figure 3 shows site attenuation versus frequency for separation distances (S) of 3 m, 10 m, and 30 m. Heights scanned are 1 m to 4 m at the 3 m and 10 m separation distances and 2 m to 6 m at the 30 m separation distance except for vertical polarization when the half-length of the receiving dipole exceeds the dipole height. The lower tip of the vertically polarized dipole is always positioned 5 cm, or more, above the ground.

Calculated site attenuation provides an ideal reference. Deviations of measured data from the reference indicate site imperfections or dipole failure.

3. Measurements

Figure 4 shows the measurement procedure used for determining site attenuation. The reference insertion loss, figure 4(a), is a received signal level, expressed in dBm, dependent upon the output level of the signal

generator and balun, cable, and attenuator losses. The output level remains fixed during the measurement procedure and is somewhat arbitrary. It is less than the maximum level acceptable by the receiver but great enough so the signal level in figure 4(b) is well above the ambient noise level.

Implicit in the measurement technique is the assumption that the signal generator output level is constant for both the reference insertion loss measurement and the site attenuation measurement at the measurement frequency. That is, it is assumed that the incident power at the 3 dB attenuator (pad) port is constant for the two measurement conditions. The signal generator used for these measurements contains an automatic level control, ALC, and it is assumed that this circuit works perfectly for the small load VSWR variation (estimated to be 5 percent or less) occurring between the two measurement conditions [3]. The incident power may be monitored using directional couplers and a power meter but these devices are not considered necessary when using high quality signal generators with ALC.

The dipole antennas have hybrid junctions for antenna baluns. Equal length coaxial cables from the dipole terminals to the hybrid junction form a 100 ohm, balanced, shielded transmission line. As a result, the receiving and transmitting system impedances are 100 ohms. This value is used to calculate the reference site attenuation data shown in figure 3 as the solid lines for very thin dipoles and (+) points for dipoles with dimensions of those actually used for the measurements. To insure that this impedance is 100 ohms, miniature 3 dB attenuators are permanently installed in the four separate cables at the point of attachment to the dipole terminals.

The receiving dipole is moved up and down over the specified height range by a person below the ground screen who observes the receiver display. The maximum received signal level is recorded by a peak sample-and-hold circuit in the receiver. The magnitude of the difference between the reference insertion loss value and this maximum measured value gives site attenuation directly. No additional measurements or corrections are required. The measured data are shown as the circles in figure 3.

4. Error Estimate

Test range antenna heights and separation distances are set within ±1 cm assuming the ground screen surface is perfectly flat. Dipole height is measured at the dipole feedpoint. Calculated errors in site attenuation are at most ±0.09 dB as a result of possible positioning errors. The extensible dipoles used at 97 MHz and lower frequencies droop about 16 cm at the tips at 30 MHz. No effort is made to keep these dipoles straight and the resulting error, discussed in Appendix I, is negligible.

The stability of the combination of the receiver, signal generator, hybrid junctions, and cables is determined by the repeatability of the reference insertion loss measurements, figure 4(a), performed before and after each subset of measurements. (The three subsets of measurement frequencies are determined by the frequency ranges of the three sets of hybrid junctions). Over these typically two hour time periods, the difference between the initial and final reference insertion loss data is at most ±0.11 dB. This variability appears to be predominantly caused by cable handling, connector mating, and moving the signal generator. Since this is a relative measurement, not an absolute one, the primary accuracy limitation is the manufacturer's specified "cumulative fidelity" for the receiver (spectrum analyzer) of "< ±1.0 dB over 0 to 80 dB display, 20-30° C." Errors in calculated mismatch loss at the 3 dB attenuators is discussed in Appendix I. The inability of the 3 dB attenuators to force the signal source and receiving system reflection coefficients to 0 results in estimated errors of 0.27 dB, 0.17 dB due to source system VSWR and 0.1 dB due to receiving system VSWR. Therefore, a simple worst case error estimate gives (±0.09±0.11±1.0±0.27) = ±1.47 dB. The largest single error, that of the receiver cumulative fidelity, can be reduced by carefully calibrating the receiver.

The average difference between the measured and calculated (calculated - measured, dB) data for horizontal polarization is -0.2 dB with a standard deviation of 0.4 dB calculated using the dB values. For vertical polarization, these statistics are 0.03 dB and 0.86 dB respectively. The greatest difference between measured and calculated site attenuation is 1.02 dB for horizontal polarization, where the effect of feed cable reflections is negligible, and 1.94 dB for vertical polarization.

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The data for the single measurement set upon which this paper is based are shown in Table 1. This was the first set of data measured after the preliminary set used to determine the suitability of the various test components. Failure of the air-supported fabric cover over the NBS ground screen facility has temporarily halted further measurements.

5. Conclusions

The agreement between measured and calculated site attenuation data is good, even for vertical polarization. The good agreement for vertical polarization is believed to result from the use of commercial hybrid junctions as dipole antenna baluns. These devices split the E port power 180° ±1° at the 1 and 2 ports. Little or no unbalanced (common mode) current flows on the feed cables and produces unwanted radiation.

Implementation of the deceptively simple mutual impedance equations is actually a fairly straightforward computer programming exercise. To relieve interested readers of this exercise, Appendix II contains Program ZMM1, the listing of the FORTRAN 4 code used to calculate site attenuation. No claim is made for the efficiency or structure of the code or its accuracy beyond the comparison of measured and calculated results presented here.

The actual measurement technique is certainly not new. It is basically a "two identical antenna" gain measurement that stops short of the last step -- subtracting the path loss and mismatch loss from the measured data to obtain the product of the gain of two identical antennas over ground.

6. References

[1]   King, H.E., "Mutual impedance of unequal length antennas in echelon," IEEE T-AP-5, pp. 306-313, July 1957.

[2]   Schelkunoff, S.A., and Friis, H.T., Antennas, Theory and Practice, New York: Wiley, 1952, Ch. 13, pp. 431-434.

[3]   Engen, G.F., "Amplitude stabilization of a microwave signal source," IEEE T-MTT-6, pp. 202-206, April 1958.

Table 1. Measured and Calculated Site Attenuation Data, dB

Horizontal Polarization

Frequency, MHz	3 m Distance		10 m Distance		30 m Distance	
	meas.	calc.	meas.	calc.	meas.	calc.
30.0	10.3	10.182	22.1	21.238	34.3	33.461
44.0	10.8	10.357	20.9	20.912	35.7	35.850
65.0	11.6	11.389	22.6	22.332	35.6	35.350
97.0	13.1	13.124	22.1	22.446	34.6	34.689
143.0	17.0	17.142	25.9	26.261	36.2	36.630
210.0	20.9	20.954	29.3	29.527	39.0	39.057
311.0	23.9	23.903	32.7	32.455	42.3	41.977
459.0	27.7	27.401	36.4	36.370	45.5	45.435
677.0	31.1	30.720	40.8	39.777	49.4	49.078
1000.0	35.0	34.045	43.5	43.112	53.4	52.439

Vertical Polarization

Frequency, MHz	3 m Distance		10 m Distance		30 m Distance	
	meas.	calc.	meas.	calc.	meas.	calc.
44.0	12.3	12.312	17.9	18.507	25.2	26.014
65.0	14.7	15.286	20.1	20.782	28.0	28.508
97.0	19.1	19.438	23.1	24.295	31.6	32.530
143.0	20.9	20.268	29.0	27.909	36.7	36.152
210.0	22.8	23.412	30.7	31.529	38.5	40.437
311.0	26.4	26.798	34.9	33.998	46.1	44.459
459.0	30.2	30.212	37.5	36.998	46.3	46.068
677.0	33.4	33.531	41.0	40.202	50.6	49.230
1000.0	37.7	36.961	44.2	43.779	51.7	52.576
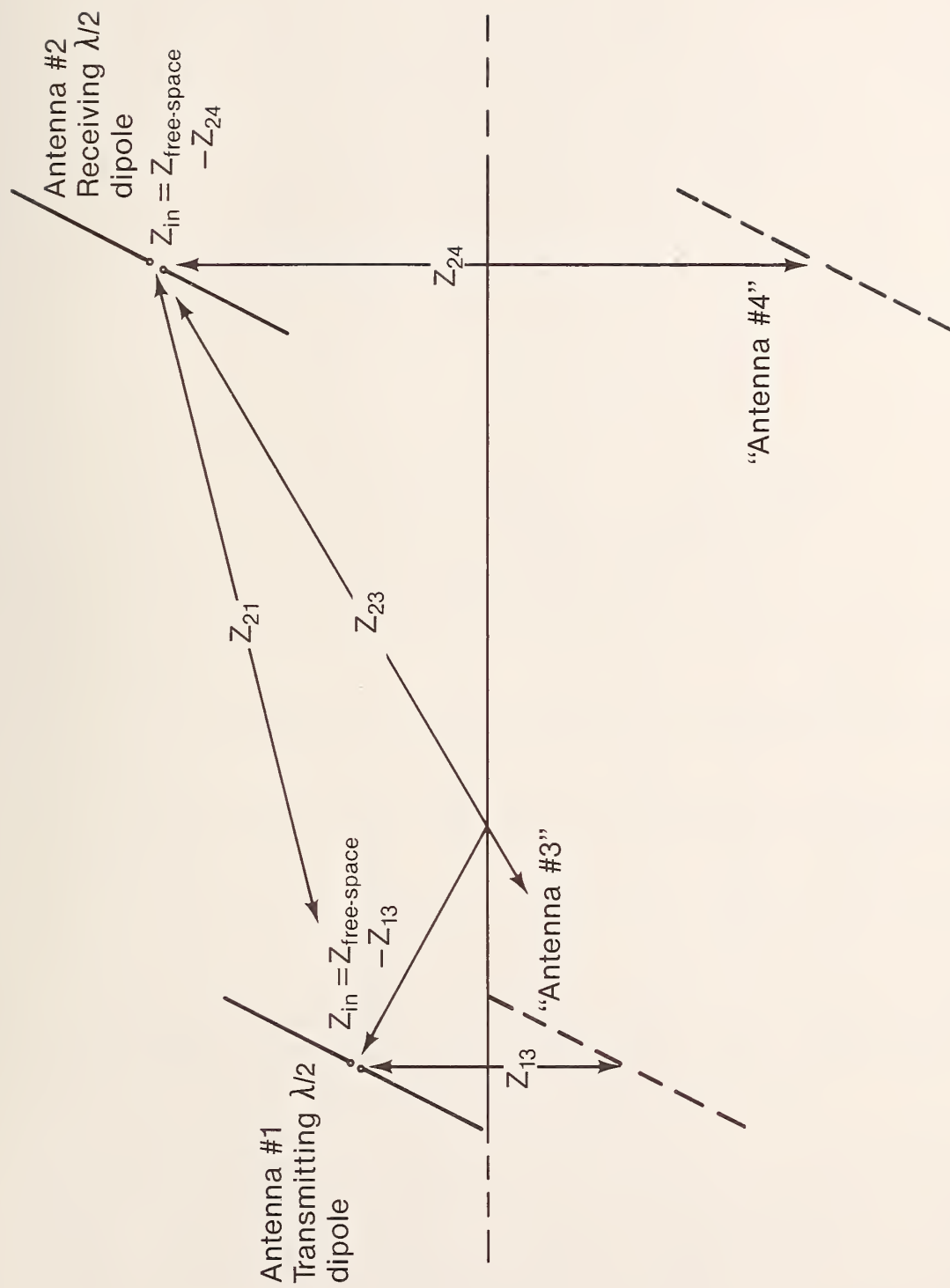
Figure 1. Test range geometry and the impedance relationships for horizontal dipole antennas.
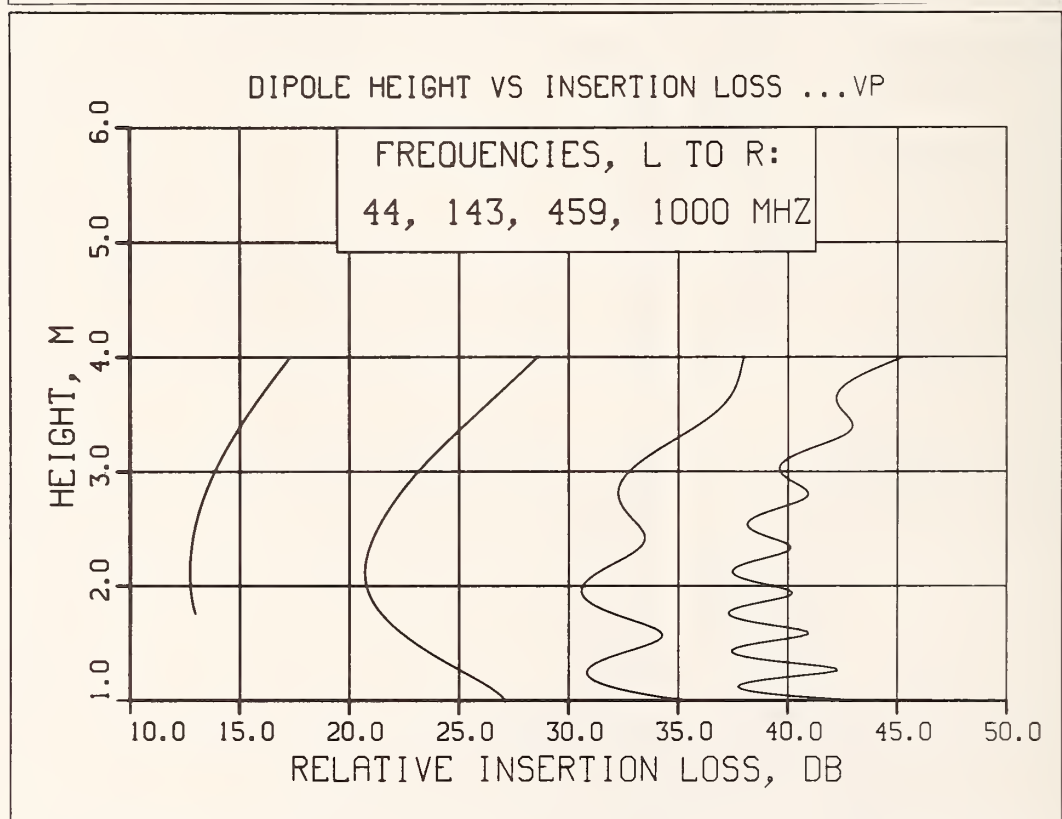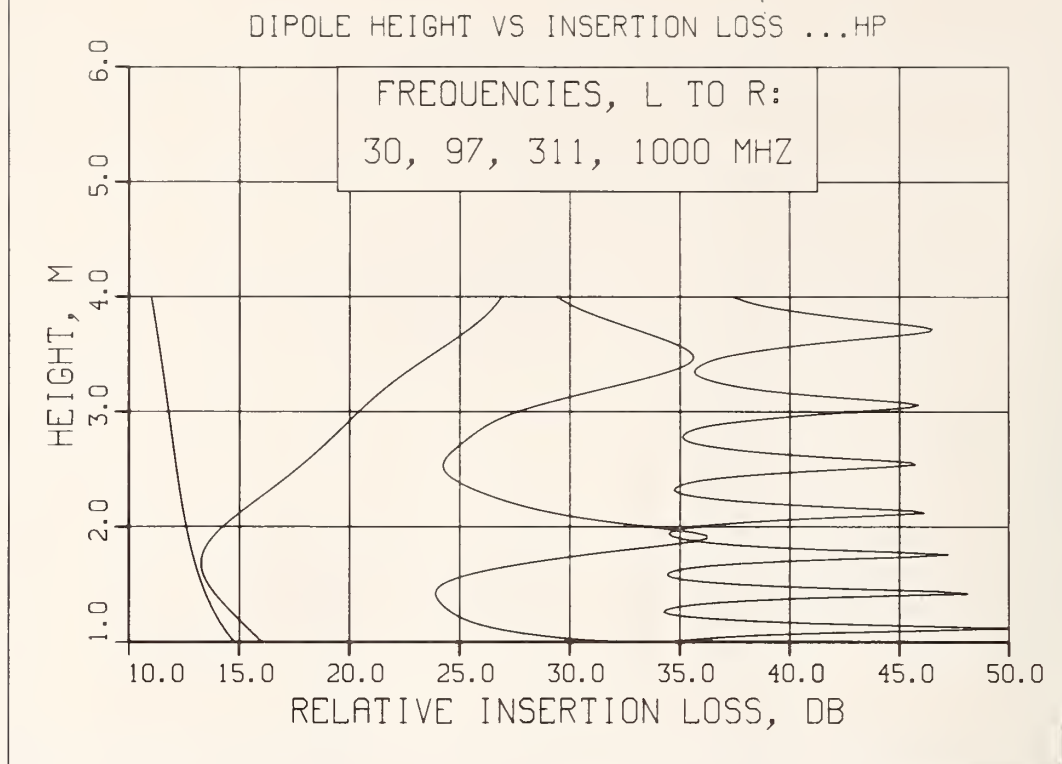
Figure 2. Selected relative insertion loss data calculated for horizontally polarized, HP, and vertically polarized, VP, dipoles over perfect ground. Site attenuation is the single minimum relative insertion loss value of each curve. Separation distance is 3 m; transmitting dipole height is 2 m.
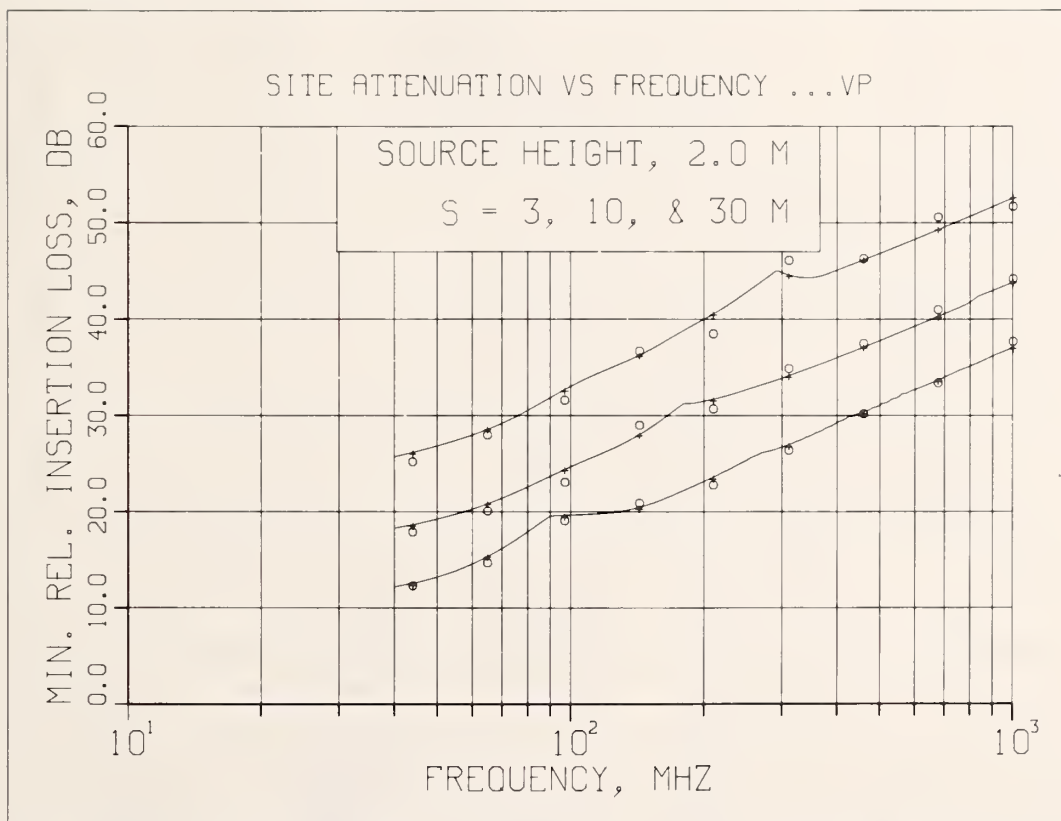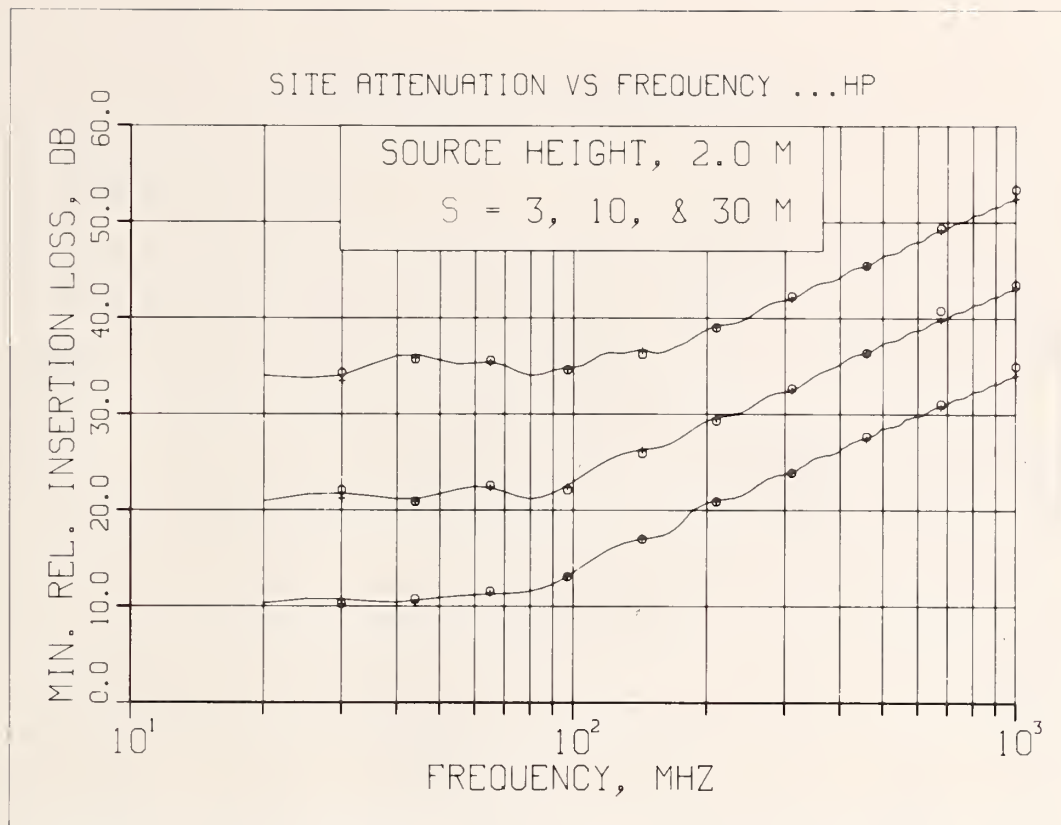
Figure 3. Site attenuation for horizontally polarized, HP, and vertically polarized, VP, dipoles over perfect ground. Solid curves are calculated for half-wave dipoles with radius = 1.E-30 m; + + points are calculated for dimensions of actual dipoles. Measured data are shown as o o.

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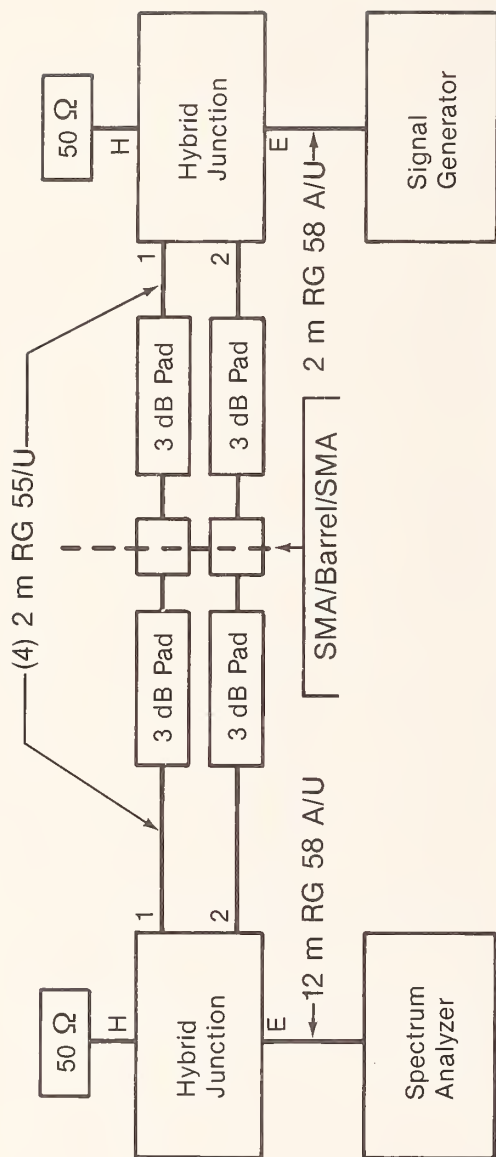
(a) Measure reference insertion loss
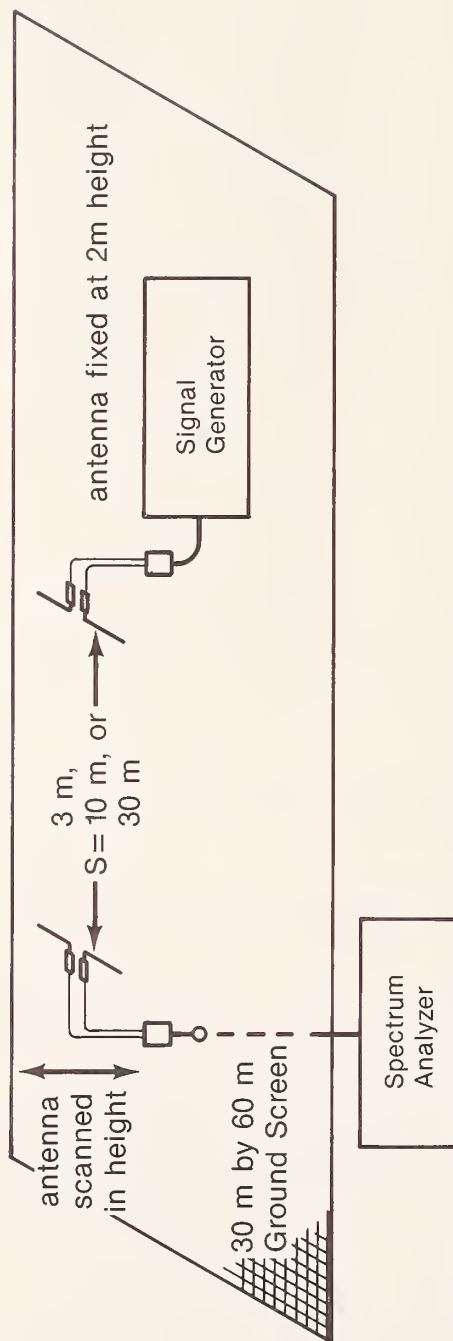
(b) Measure reference insertion loss plus site attenuation

Figure 4. Schematic diagram of measurement procedure.

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Appendix I. The Dipole Antennas

1. Physical Characteristics

Figures 1A through 4A are photographs showing the dipole antenna fabrication details. The 2.54 cm diameter white teflon feedpoint assembly is machined from a 8.89 cm length of rod stock. A cylindrical hole 2.22 cm long, 1.27 cm wide, and 1.31 cm deep provides room for the SMA panel jacks which form the dipole feedpoint. A flat surface opposite this hole supports the panel jack nuts. These dimensions are chosen to allow a nut driver to fit on the panel jacks during tightening, allow just enough separation between the panel jacks for attaching SMA connectors, and give a sufficient thickness of teflon to support the panel jacks yet allow the SMA connectors to seat full depth on the jack body. Another flat surface, 90 deg around the feedpoint assembly with a centered hole, provides the mounting surface for a 2.54 cm diameter wood dowel used as the antenna mast.

The ends of the feedpoint assembly are drilled to a 1 cm diameter to form holes 2.64 cm deep. These holes provide a press fit for the extensible dipole elements used from 30 MHz to 97 MHz. Small holes are drilled in the center of the bottom of these 1 cm holes into the feedpoint cylinder and tapped with 6-32 threads. Stock banana plugs (13/16 in x 6-32, threaded shank) are screwed into place and the threaded shank is soldered to the panel jack center pin. A solder bridge is formed to join the outer conductor hexagonal surfaces of the panel jacks as shown in figure 3A; figure 4A shows the banana plug in the 1 cm diameter hole. The ends of the extensible dipole elements are drilled with a hole for a snug fit over the banana plug. These extensible elements are four section stainless steel whips with a 68.58 cm minimum length and a 243.84 cm maximum length.

None of the dimensions are critical to the electrical performance of the dipole. Basically, the feedpoint assembly is made from a low loss dielectric material that is strong enough to support the 30 MHz half-wave elements and provide a feedpoint gap that is much smaller than a wavelength at the highest frequency of interest. Dipole elements for the frequencies above 97 MHz are fixed lengths of thin wall brass tubing having a 0.48 cm outer diameter. These elements are supported by the banana plug and a 1 cm diameter dielectric washer positioned at the end of the feedpoint assembly.

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Antenna half-length, measured from the center of the feedpoint assembly, is approximately one-half wavelength. It is chosen so that the calculated free-space input impedance is purely real. These lengths are determined using Program HVD3 which is included in Appendix II.

The 50 ohm coaxial hybrid junctions, serving as antenna baluns, are four-port devices having the following minimum performance specifications:

1. Isolation: 30 dB
2. Phase balance, E (diff) port feed: 180 deg ± 1 deg
3. Amplitude balance: 0.2 dB
4. VSWR: 1.3
5. Insertion loss, E(diff) port feed: 0.75 dB.

Equal length coaxial cables, 2 m long, separate the hybrid junctions from the feedpoint assembly. These cables are cut physically the same length from a single spool of cable and the connectors are carefully attached according to the manufacturer's instructions. Insertion loss versus frequency of two cable-hybrid junction assemblies is measured between the E ports. The H ports are terminated with 50 ohm loads. The cable pair attached to the colinear ports of the hybrid junctions form a shielded, balanced, 100 ohm transmission line. Satisfactory performance is observed when the measured insertion loss is a smooth function of frequency and approximately equal to the cable loss plus the hybrid junction insertion loss.

2. Mismatch Loss

As mentioned in the main body of the text, high performance, miniature 3 dB attenuators having maximum VSWR specifications of 1.07 + 0.015f(GHz), DC to 8 GHz are permanently attached to the equal length cables at the dipole feedpoint. The attenuators reduce the errors incurred in assuming the source and receiving system impedances are exactly 100 ohms in the site attenuation calculation. These impedances are not exactly 100 ohms because the source signal generator is specified to have a VSWR ≤ 2 and the receiver is specified to have a VSWR ≤ 1.5.

A commercial computer software package, "General Microwave Circuit Analysis Program" [A1], is used to determine the input VSWR at the attenuator ports attached via one of the equal length cables to the hybrid junction and the source signal generator or receiver as shown in figure 5A. The attenuator and hybrid

junction are modeled with resistive "T" networks to match manufacturer specifications. The signal generator is modeled with 25 ohm and 100 ohm resistors and the receiver is modeled with 33.3 ohm and 75 ohm resistors. Worst case input VSWR values occur at 44 MHz (calculations use the 10 test frequencies) and the smaller of the two resistive values representing receiver and source signal generator impedances. Without the 3 dB attenuators, the source circuit input VSWR is 2.01 and the receiving circuit input VSWR is 1.64. With the attenuators, these VSWR values are 1.5 and 1.4 respectively. The mismatch losses resulting from these non-perfect input impedances are the magnitudes of the errors which may occur if the worst case conditions are realized; 0.17 dB and 0.1 dB respectively. Therefore, a total worst case error of 0.27 dB may occur because the impedances of the source and receiving circuitry attached to the dipole terminals are not exactly 50 ohms at each attenuator. Larger attenuators will reduce these errors even more if the reduced signal levels can be tolerated during the site attenuation measurements.

The conjugate mismatch loss, M_L (referred to simply as mismatch loss in this paper) is calculated as follows [A2]:

$$M_L = 10 \log_{10} \frac{|1 - \Gamma_s \Gamma_a|^2}{(1 - |\Gamma_s|^2)(1 - |\Gamma_a|^2)} , \qquad (1A)$$

where Γ_s = complex reflection coefficient of the source circuitry, and

Γ_a = complex reflection coefficient of the antenna.

Forcing the source VSWR to 1 with large enough attenuators, i.e., forcing $\Gamma_s = 0$, gives

$$M_L = 10 \log_{10} \frac{1}{1 - |\Gamma_a|^2} . \qquad (2A)$$

Computer Program HVD3 evaluates this expression using

$$\Gamma_a \equiv R = (ZR - ZCHAR)/(ZR + ZCHAR) , \qquad (3A)$$

where ZR = dipole input impedance, and

ZCHAR = 100 ohms, the receiving or source system impedance.

Tuning devices may be used at fixed frequencies to force Γ_s to zero but this technique is not normally used for antenna measurements over a wide range of frequencies.

3. Input Impedance

Dipole input impedance is calculated using well documented equations. "Aside from the shunt admittance of the input region, which may or may not be significant, the input impedance of the antenna is" [A3]:

$$Z_i = K_a \frac{(K_a - M) \cos \beta\ell + j(Z_a + j\omega C_t K_a^2 - jN) \sin \beta\ell}{(Z_a + j\omega C_t K_a^2 + jN) \cos \beta\ell + j(K_a + M) \sin \beta\ell} , \qquad (4A)$$

where $K_a = 120 \ln \frac{2\ell}{a_b} + \frac{120 \, a_t}{a_b - a_t} \ln \frac{a_t}{a_b}$,

a_t = radius of tip of linearly tapered antenna ,

a_b = radius of base of linearly tapered antenna ,

or $\qquad K_a = 120 \, (\ln \frac{2\ell}{a_t} - 1)$ for $a_t = a_b$,

ℓ = dipole half length ,

$M = 60 \, (Cin \, 2\beta\ell - 1 + \cos 2\beta\ell)$,

$N = 60 \, (Si \, 2\beta\ell - \sin 2\beta\ell)$,

$\beta = 2\pi/\lambda$,

$Cin \; x = \int_0^x \frac{1 - \cos t}{t} \, dt$,

$Si \; x = \int_0^x \frac{\sin t}{t} \, dt$,

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$$j\omega\, C_t = \frac{ja_t}{30\lambda} \; ,$$

$$Z_a = R_a + j\, X_a \; ,$$

$$R_a = 60\, \text{Cin}\, 2\beta\ell + 30(2\, \text{Cin}\, 2\beta\ell - \text{Cin}\, 4\beta\ell)\, \cos 2\beta\ell$$
$$+ 30(\text{Si}\, 4\beta\ell - 2\text{Si}\, 2\beta\ell)\, \sin 2\beta\ell \; ,$$

and $\quad X_a = 60\, \text{Si}\, 2\beta\ell - 30(\text{Cin}\, 4\beta\ell - \ell n4)\sin 2\beta\ell - 30\, \text{Si}\, 4\beta\ell \cos 2\beta\ell \; .$

These equations appear in lines 1070 - 1180, Program HVD3 and lines 1600 - 1710, Program ZMM1, both in Appendix II, and apply only to straight dipoles.

4. Dipole Droop

Unfortunately, real dipoles droop at the lower frequencies considered in this paper. A relatively new computer program does enable the calculation of gain pattern and input impedance of arbitrary wire antennas of finite dimensions over perfect ground. Drooping dipole input impedance can be calculated using this program, called MININEC, which is a small version of a larger numerical electromagnetics code [A4, A5].

The profile of the actual 30 MHz dipole was measured and the resulting MININEC model utilizes eight wires, one for each telescoping section comprising the antenna. Each of the 8 wires is represented by 10 equal length segments. Currents on the wire are expanded in pulses centered at the junctions of adjacent segments.

MININEC must be used carefully and enough segments selected to insure near convergence of the input impedance data. Table 1A shows input impedance data calculated for the 30 MHz tapered dipole used for the site attenuation measurement. Input impedance data for the straight dipole calculated using Schelkunoff's equations are included for interest and entitled HVD3, straight. This is the "worst case" dipole because it is physically the longest, has the most droop, and is electrically closest to the ground. Since MININEC and HVD3 give slightly different input impedances for the straight dipoles over perfect ground, the effect of droop is approximated by comparing the difference in

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Table 1A. Calculated Input Impedance for Horizontal, 30 MHz, Half-Wave Dipoles Over Perfect Ground

Half-length = 2.4 m

Tip radius = 0.0013 m

Base radius = 0.005 m

Calculation, Geometry	Height, m	Zin, ohms	Mismatch Loss, dB
HVD3, straight	2	60.1 + j33.1	0.46
	4	82.1 - j11.0	0.06
	6	52.2 - j 2.0	0.45
	∞	65.7 - j 0.3	0.19
MININEC, straight	2	62.8 + j 2.3	0.23
	4	79.9 - j44.8	0.32
	6	51.5 - j32.7	0.67
	∞	65.0 - j32.3	0.36
MININEC, drooping	2	62.9 + j 6.8	0.24
	4	81.2 - j41.6	0.27
	6	51.7 - j30.0	0.63
	∞	65.5 - j29.1	0.33

Note: It would require an uneconomical amount of computer time to determine Zin continuously versus height above ground for both straight and drooping 30 MHz dipoles. The 0.05 dB mismatch loss difference, attributable to dipole droop, is assumed to be the worst case value.

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impedances, more specifically the difference in mismatch loss, between the MININEC results. This difference is at most 0.05 dB and is considered negligible.

Dipole droop will slightly change the effective height of the dipole above ground. However, the current distribution is sinusoidal, not linear, and the least drooped sections support the greatest current density. This, together with the fact that the site attenuation measurement utilizes height scanning, means that the exact height is not important. Figures 6A and 7A show the height versus frequency at which the site attenuation data are calculated.

5. The Mutual Impedance of Dipoles in Echelon

In contrast to the input impedance calculations, King [A6] states that "the mutual impedance equations apply accurately to infinitely thin antennas only, but nonetheless serve as a practical approximation for real antennas of finite thickness". Half-wave dipoles were chosen for the site attenuation measurements because their performance parameters are calculable. Professor Jordan states, "Inasmuch as the actual current distribution is known to be very nearly sinusoidal for thin transmitting antennas (dipoles and monopoles), the (calculated radiated field) obtained is a good approximation to the true power radiated" [A7]. For receiving dipoles he states, "For a resonant-length half-wave receiving dipole, the current distribution is found to be sinusoidal and, to a first approximation, the current amplitude is independent of the thickness of the antenna" [A7, p. 549]. Finally he assigns a problem which completes these comments on the current distribution of half-wave dipoles as follows:

> "The current distribution in a half-wave transmitting antenna is
> known to be nearly sinusoidal. The current distribution of a
> half-wave dipole receiving antenna is also nearly sinusoidal when
> the terminals are short-circuited. Using the superposition and
> compensation theorems, verify that the current distribution of the
> half-wave dipole as a receiving antenna must be approximately
> sinusoidal when the terminals are connected to any load impedance
> Z" [A7, p. 338].

Therefore, calculated site attenuation based almost entirely upon King's mutual impedance formulations and sinusoidal current distribution gives a good reference model when half-wave dipoles are employed.

Subroutine ZZ in Program ZMM1, Appendix II, is used to calculate 18 arguments for sine and cosine integrals required by the mutual impedance equations. Ninety-six of these integral terms are used in the general formulations to obtain the mutual impedance referred to the loop current. The mutual impedance referred to the base current is the quantity needed to evaluate dipole input impedance, the power transmitted, and the power received. Professor Jordan also discusses the relations between the base and loop current references for input and mutual impedance calculations [A7,p. 345-351]. This change of reference is implemented in Program ZMM1 line 03970 as follows:

```
Z12B (K) = Z12L(K)/((SIN(BETA*L))**2)
```

where Z12B is the mutual impedance referred to the base current and Z12L is the mutual impedance referred to the loop current.

Since Program ZMM1 calculates site attenuation for both vertical and horizontal dipoles, the reversal of the apparent current direction in the image dipole for horizontal polarization is handled in lines 03940 to 03960.

Subroutine MUTUAL, used to compute the mutual impedance between the dipoles and their images in perfect ground, uses a subset of the general formulations given in Subroutine ZZ. These two subroutines were developed separately and left that way for clarity. Subroutine MUTUAL could be replaced with a call to Subroutine ZZ if ZZ were modified to handle the call. This would shorten the program substantially.

The sine and cosine integrals are evaluated using series expansion equations given in Abramowitz and Stegun [A8]. The computer implementation of these equations was developed many years ago and different ones may be available in mathematical software packages. As noted in Program ZMM1, a linear interpolation is imposed to smooth the functions in the transition region occurring between the large argument and small argument approximations to these integrals.

References for Appendix I

[A1]   Tektronix Product Number 4050A06, Tektronix, Inc., Beaverton, OR; 1975.

[A2]   Beatty, R.W., "Insertion loss concepts," Proc. IEEE, Vol. 52: 663-671; 1964 June.

[A3]   Schelkunoff, S.A., Friis, H.T., Antennas, Theory and Practice, New York, NY: John Wiley & Sons; 1952. 431-434.

[A4]   Julian, A.J., Logan, J.C., Rockway, J.W., "MININEC: A mini-numerical electromagnetic code," Tech. Doc. 516, Naval Ocean Systems Center, San Diego, CA; 1982 6 Sept.

[A5]   Campbell, D.V., "Personal computer applications of MININEC," IEEE AP-S Newsletter, Vol. 26; 1984 February.

[A6]   King, H.E., "Mutual impedance of unequal length antennas in echelon," IEEE T-AP-5, pp. 306-313; July 1957.

[A7]   Jordan, E.C., Electromagnetic Waves and Radiating Systems, Englewood Cliffs, NJ: Prentice-Hall; 1950. p. 365.

[A8]   Abramowitz, M., Stegun, I.A., Handbook of Mathematical Functions With Formulas, Graphs, and Mathematical Tables, Washington, DC; Nat. Bur. of Stand. (U.S.) Applied Mathematics Series 55; 1964; pp. 231-233.

Figure 1A. The dipole assemblies showing telescoping elements in one and fixed length elements in the other. Hybrid junction and cables are attached to the feedpoint assembly with the short, fixed length elements.

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Figure 2A. A close view of a dipole assembly showing the 3 dB attenuators attached at the white teflon feedpoint assembly.

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Figure 3A. The feedpoint assembly showing dipole feedpoint region.

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Figure 4A. The feedpoint assembly showing tip of banana plug.
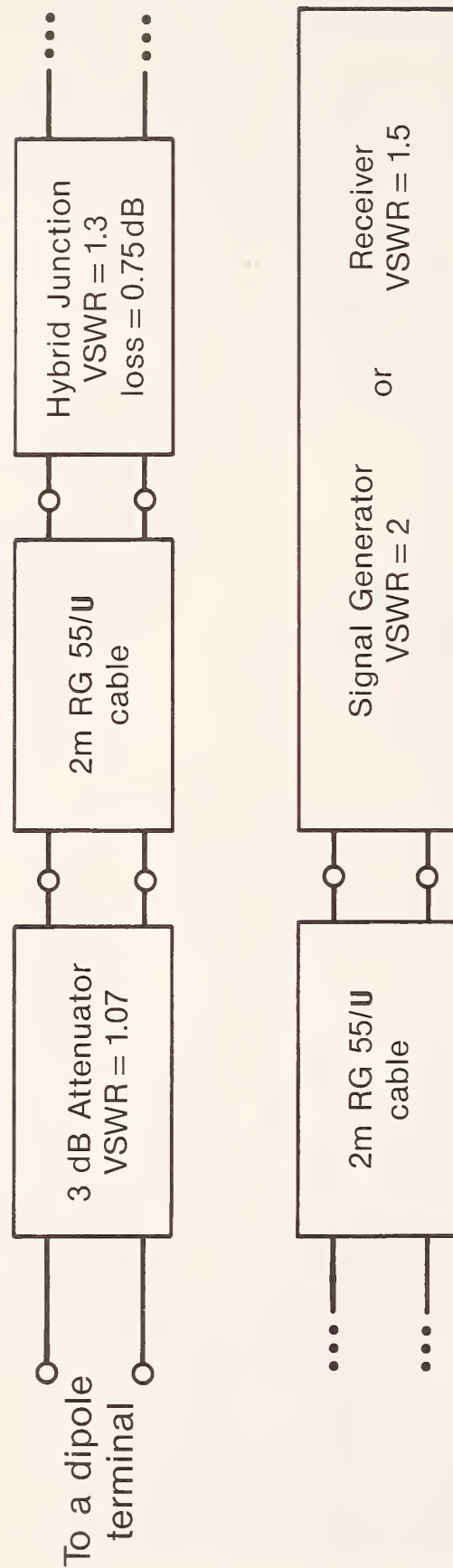
Figure 5A. Schematic diagram of two-port circuits representing the effective source signal generator and receiver circuits.
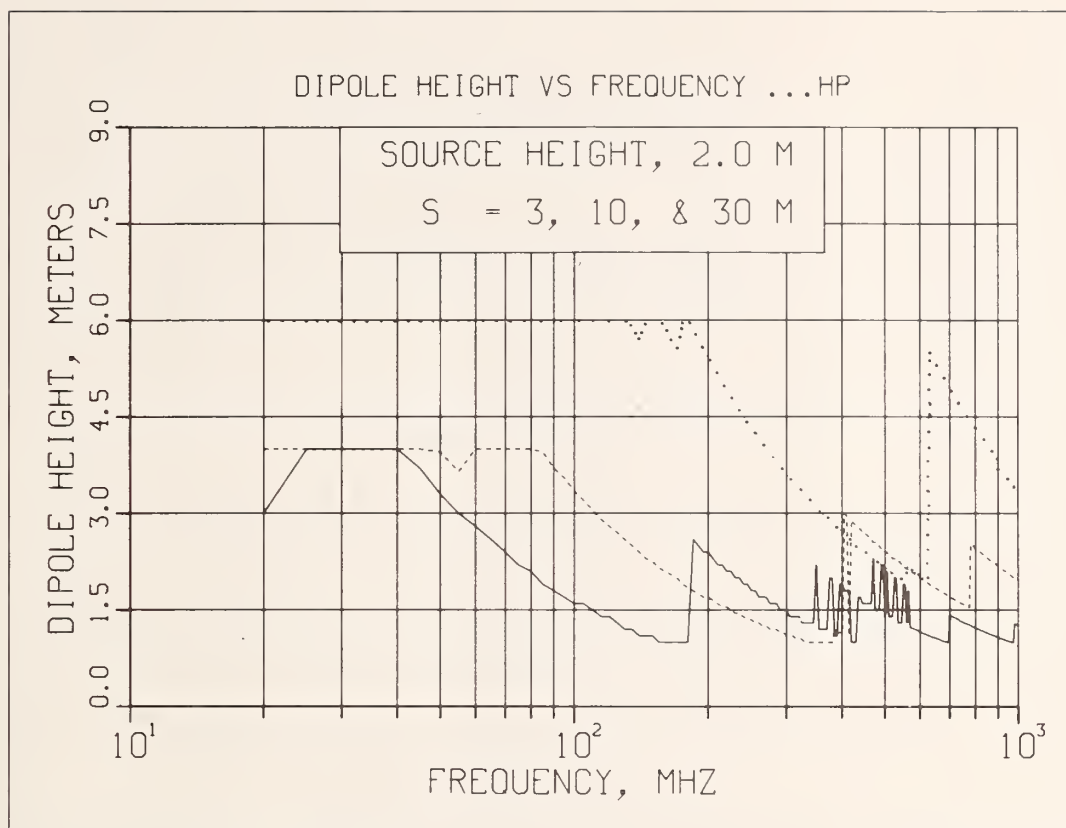
Figure 6A. Heights versus frequency for which site attenuation is calculated for horizontal dipoles.

        Solid line   -   3 m separation distance
        Dashed line -   10 m separation distance
        Dotted line -   30 m separation distance.
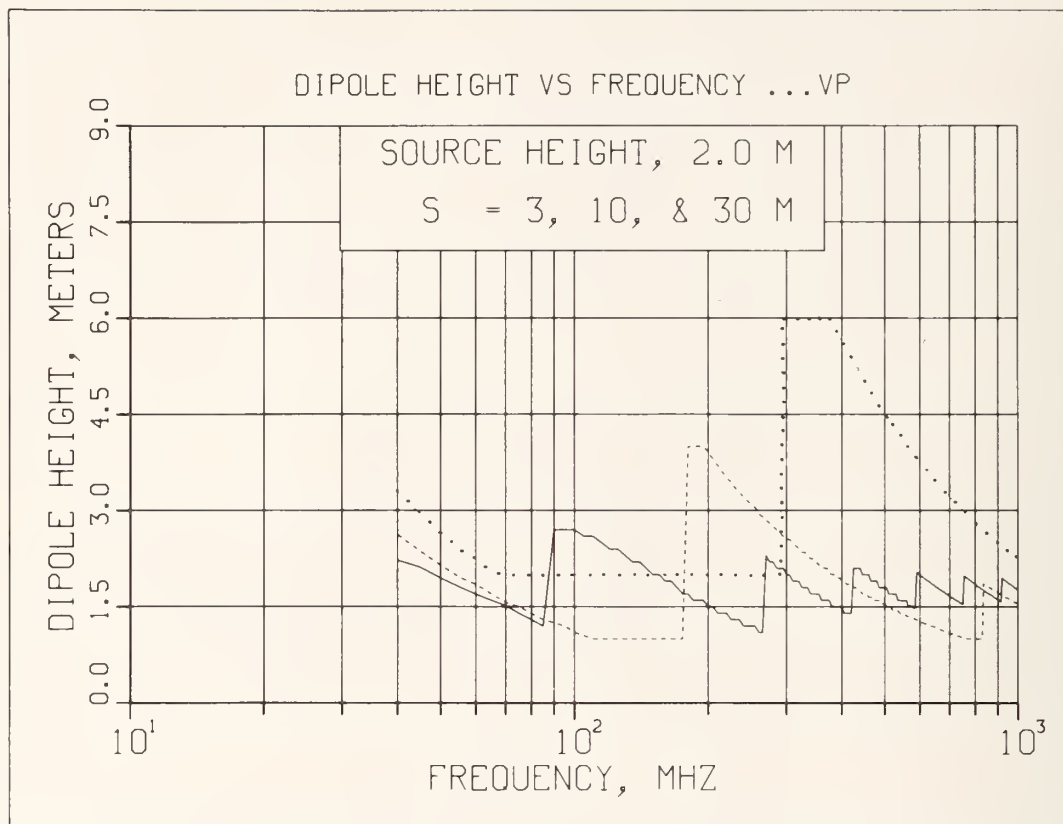
Figure 7A. Heights versus frequency for which site attenuation is calculated
for vertical dipoles.

Solid line   –   3 m separation distance
Dashed line   –   10 m separation distance
Dotted line   –   30 m separation distance.

APPENDIX II

Computer Program HVD3

and

Computer Program ZMM1

```
00100 PROGRAM HVD3(INPUT,OUTPUT)
00110C***********************************************************************
00120C*    GAIN VS. ELEVATION ANGLE FOR VERTICAL AND HORIZONTAL DIPOLES  *
00130C*    OVER GROUND AND FOR MONOPOLES OVER PERFECT GROUND.  NOTE:      *
00140C*    SCHELKUNOFF'S MODE THEORY IS USED TO CALCULATE FREE SPACE      *
00150C*    ANTENNA IMPEDANCE.  IF THE DIPOLE FEEDPOINT HEIGHT IS WITHIN    *
00160C*    0.1*LAMBDA OF THE GROUND, THE SELF IMPEDANCE OF THE ANTENNA     *
00170C*    IS CALCULATED USING THE MUTUAL IMPEDANCE WITH 0.0001*LAMBDA     *
00180C*    SEPARATION BECAUSE USE OF SCHELKUNOFF'S SELF IMPEDANCE          *
00190C*    MAY RESULT IN NEGATIVE INPUT IMPEDANCES.  ANTENNA RADII MAY     *
00200C*    BE ZERO OR THE ANTENNA MAY HAVE A LINEAR TAPER FROM THE         *
00210C*    FEEDPOINT TO THE END.                                          *
00220C***********************************************************************
00230 DIMENSION SI(2),CIN(2),S(21),C(21),T(44),Z(2)
00240 COMPLEX CT,E,J,NBL,R,RH,RV,RH90,RV90,TSQ,ZA,ZIND,ZINN,ZM,ZR,ZI,ZM1
00250 REAL KA,LAMBDA,L,L2,LOSS,MBL,MONO
00260C*******************************************************
00270C*    THE USER SPECIFIES THE ANTENNA GEOMETRY  *
00280C*                                             *
00290C*    NOTE: FOR A MONOPOLE (FED AGAINST PERFECT*
00300C*    GROUND ONLY) THE CONDUCTIVITY MUST BE    *
00310C*    SET TO ZERO.                             *
00320C*******************************************************
00330 1 CONTINUE
00340 2 FORMAT(*TYPE THE REQUESTED DATA AFTER EACH ?
00350+           FREQUENCY, MHZ*)
00360 PRINT 2
00370 3 FORMAT(F12.4)
00380 READ 3,FREQ
00390 4 FORMAT(*ANTENNA HALF-LENGTH, M, LAMBDA/4 OR LESS*)
00400 PRINT 4
00410 READ 3,L
00420 5 FORMAT(*ANTENNA RADII, END THEN FEEDPOINT, M*)
00430 PRINT 5
00440 READ 3,RT
00450 READ 3,RB
00460 IF(RT.EQ.0.AND.RB.EQ.0)RT=1.E-30
00470 IF(RT.EQ.1.E-30)RB=1.E-30
00480 6 FORMAT(*GROUND CONDUCTIVITY, MILLIMHOS/M*)
00490 PRINT 6
00500 READ 3,SIGMA
00510C***********************************************************************
00520C*    PERFECT GROUND AND FREE-SPACE APPROXIMATIONS ARE MADE.  *
00530C***********************************************************************
00540 IF(SIGMA.GE.10000000.0) SIGMA = 1.E30
00550 IF(SIGMA.GE.10000000.0) EPSILON = 1.0
00560 IF(SIGMA.GE.10000000.0) GO TO 8
00570 IF(SIGMA.EQ.0.) EPSILON = 1.
00580 IF(SIGMA.EQ.0.) H=1.E-30
00590 IF(SIGMA.EQ.0.) GO TO 10
00600 7 FORMAT(*GROUND RELATIVE DIELECTRIC CONSTANT*)
00610 PRINT 7
00620 READ 3,EPSILON
00630 8 CONTINUE
00640 9 FORMAT(*DIPOLE FEED-POINT HEIGHT ABOVE GROUND, M*)
00650 PRINT 9
00660 READ 3,H
00670 10 CONTINUE
00680 11 FORMAT(*IMPEDANCE OF T-LINE ATTACHED TO ANTENNA, OHMS*)
00690 PRINT 11
00700 READ 3,ZCHAR
00710 J = CMPLX(0.,1.)
00720 LAMBDA = 299.792458/FREQ
00730 BETA = 6.2831853/LAMBDA
```

```
00740C*******************************
00750C*  THE CALCULATIONS BEGIN HERE  *
00760C*******************************
00770 12 B = 2.*BETA*L
00780 BL = BETA*L
00790 BH = BETA*H
00800 X = 18.*SIGMA/FREQ
00810 Y = EPSILON
00820C***************************************************
00830C*  COMPUTE SINE AND COSINE INTEGRALS FOR SELF   *
00840C*  IMPEDANCE CALCULATION, SI(M) AND CIN(M)      *
00850C***************************************************
00860 20  K = 1
00870 T(1) = 1.0
00880 DO 30 M = 1,42
00890 K = K  + 1
00900 30  T(K) = M*T(K-1)
00910 DO 60 M=1,2
00920 Z(M) = M*B
00930 DO 40 N = 1,20
00940 40 S(N) = ((-1)**N)*(Z(M)**(2*N+1))/((2*N+1)*T(2*N+2))
00950 SI(M)=Z(M)+S(1)+S(2)+S(3)+S(4)+S(5)+S(6)+S(7)+S(8)+S(9)+S(10)
00960+      +S(11)+S(12)+S(13)+S(14)+S(15)+S(16)+S(17)+S(18)+S(19)+S(20)
00970 DO 50 N = 1,20
00980 50 C(N) = ((-1)**N)*(Z(M)**(2*N))/((2*N)*T(2*N+1))
00990 60 CIN(M)=-(C(1)+C(2)+C(3)+C(4)+C(5)+C(6)+C(7)+C(8)+C(9)+C(10)
01000+      +C(11)+C(12)+C(13)+C(14)+C(15)+C(16)+C(17)+C(18)+C(19)+C(20))
01010C***************************************************************
01020C*  NO LARGE ARGUMENT APPROXIMATION IS REQUIRED FOR SI AND CIN  *
01030C*  BECAUSE OF THE RESTRICTION ON THE DIPOLE LENGTH IN LINE 260  *
01040C***************************************************************
01050C*  COMPUTE SELF IMPEDANCE, ZI, USING EQN. 108 OF REFERENCE [3]  *
01060C***************************************************************
01070 IF(RT.EQ.RB)KA = 120.*(ALOG(2.*L/RT)-1.)
01080 IF(RT.NE.RB)KA=120.*(ALOG(2*L/RB)+(RT/(RB-RT))*ALOG(RT/RB))
01090 MBL = 60.*(CIN(1)-1.+COS(B))
01100 NBL = J*60.*(SI(1)-SIN(B))
01110 ZAR = 60.*CIN(1)+30.*(2.*CIN(1)-CIN(2))*COS(B)+30.*(SI(2)
01120+      -2.*SI(1))*SIN(B)
01130 ZAI = 60.*SI(1)-30.*(CIN(2)-ALOG(4.))*SIN(B)-30.*SI(2)*COS(B)
01140 ZA = ZAR+J*ZAI
01150 CT = J*RT/(30.*LAMBDA)
01160 ZINN = KA*((KA-MBL)*COS(BL)+J*(ZA+CT*KA*KA-NBL)*SIN(BL))
01170 ZIND = (ZA+CT*KA*KA+NBL)*COS(BL)+J*(KA+MBL)*SIN(BL)
01180 ZI = ZINN/ZIND
01190 62 CONTINUE
01200 64 FORMAT(*TYPE 1. FOR HORIZONTAL POLARIZATION, 0 FOR VERTICAL*)
01210 PRINT 64
01220 READ 3, POLAR
01230 MONO = 1.
01240 66 FORMAT(*TYPE 1. FOR DIPOLE OR 0 FOR MONOPOLE*)
01250 IF(POLAR.EQ.0.AND.SIGMA.EQ.0.) PRINT 66
01260 IF(POLAR.EQ.0.AND.SIGMA.EQ.0.) READ 3, MONO
01270C***************************************************************
01280C*  COMPUTE ANTENNA INPUT IMPEDANCE, ZR.  SUBROUTINE MUTUAL  *
01290C*  RETURNS THE CORRECT MUTUAL IMPEDANCE, ZM, BETWEEN TWO    *
01300C*  DIPOLES IN FREE SPACE FOR THE SPECIFIED POLARIZATION     *
01310C***************************************************************
01320 CALL MUTUAL(BETA,H,J,L,RH90,RV90,ZM,X,Y,POLAR,T)
01330 ZM1=ZM
01340 67 FORMAT(*INPUT IMPEDANCE =*F12.4*+J[*F12.4*]OHMS*)
01350 IF(H.GE.0.1*LAMBDA.OR.SIGMA.EQ.0) GO TO 68
01360 H1=0.0001*LAMBDA
01370 POLAR1=1.
```

```
01380 CALL MUTUAL(BETA,H1,J,L,DUMMY1,DUMMY2,ZM,X,Y,POLAR1,T)
01390 ZI=ZM/(SIN(BL)**2)
01400 68 CONTINUE
01410C****************************************************************
01420C*   THE ABOVE 6 LINES HELP PREVENT NEGATIVE INPUT IMPEDANCES  *
01430C*   FOR HORIZONTAL DIPOLES NEAR GROUND BECAUSE SCHELKUNOFF'S  *
01440C*   INPUT IMPEDANCE DOES NOT CONVERGE TO THAT COMPUTED BY     *
01450C*   SUBROUTINE MUTUAL.                                        *
01460C****************************************************************
01470 IF(POLAR.EQ.1.) ZR=ZI+RH90*ZM1/(SIN(BL)**2)
01480 IF(POLAR.EQ.0.) ZR=ZI+RV90*ZM1/(SIN(BL)**2)
01490 IF(MONO.EQ.0.) ZR=ZR/2.
01500 PRINT 67,ZR
01510 L2 = L
01520 81 FORMAT(*ENTER NEW HALF-LENGTH IF DESIRED, OTHERWISE ENTER 0*)
01530 PRINT 81
01540 READ 3,L
01550 IF(L.GT.0.) GO TO 12
01560 L = L2
01570C****************************************************************
01580C*   COMPUTE ANTENNA FACTOR, AF, AND OTHER IMPEDANCE RELATED   *
01590C*   PARAMETERS:  MUTUAL IMPEDANCE, VSWR, AND MISMATCH LOSS    *
01600C****************************************************************
01610 IF(MONO.EQ.0.)AF=(CABS(ZCHAR+ZR)/ZCHAR)/((1./BETA)*TAN(BL/2.))
01620 IF(MONO.EQ.1.)AF=(CABS(ZCHAR+ZR)/ZCHAR)/((2./BETA)*TAN(BL/2.))
01630C****************************************************************
01640C*   ANTENNA FACTOR = VOLTAGE DIVIDER FACTOR/EFFECTIVE LENGTH  *
01650C****************************************************************
01660 82 FORMAT(*ANTENNA FACTOR ASSUMING A *F6.2*-OHM RECEIVER*)
01670 83 FORMAT(*AND A 1:1 BALUN ARE EMPLOYED =*F8.2* DB*)
01680 84 FORMAT(*AND TRANSMISSION LINE ARE EMPLOYED =*F8.2* DB*)
01690 PRINT 82,ZCHAR
01700 IF(MONO.EQ.1.) PRINT 83, 20.*ALOG10(AF)
01710 IF(MONO.EQ.0.) PRINT 84, 20.*ALOG10(AF)
01720 90 FORMAT(*MUTUAL IMPEDANCE DUE TO THE ANTENNA'S IMAGE
01730+                         IN THE GROUND =*F12.4*+J[*F12.4*]OHMS*)
01740 IF(MONO.NE.0) PRINT 90, ZR-ZI
01750 R = (ZR - ZCHAR)/(ZR + ZCHAR)
01760 VSWR = (1.+CABS(R))/(1.-CABS(R))
01770 110 FORMAT(*VSWR =*F12.4)
01780 PRINT 110,VSWR
01790 LOSS = 10.0*ALOG10(1.0/(1.0-(CABS(R))*(CABS(R))))
01800 200 FORMAT(*MISMATCH LOSS =*F12.4* DB*)
01810 PRINT 200,LOSS
01820C*********************************************************
01830C*   COMPUTE REFLECTION COEFFICIENTS, AND THEN   *
01840C*   GAIN VERSUS ELEVATION ANGLE                 *
01850C*********************************************************
01860 300 FORMAT(*PRESS RETURN FOR GAIN VS PHI, OTHERWISE TYPE CNTL T*)
01870 PRINT 300
01880 PAUSE
01890 350 FORMAT(*ELEV ANGLE INCREMENT FOR BELOW 10 DEG AND THE
01900+                         ADDITIONAL INCREMENT FOR ABOVE 10 DEG*)
01910 PRINT 350
01920 READ 3, ENC
01930 READ 3, ENC2
01940 355 FORMAT(*HORIZONTAL POLARIZATION*)
01950 356 FORMAT(*VERTICAL POLARIZATION*)
01960 IF(POLAR.EQ.0.) GO TO 660
01970 360 FORMAT(*H-PLANE ELEVATION ANGLE IN DEGREES AND GAIN IN DB*)
01980 PRINT 360
01990 PRINT 355
02000 PSI = 0
02010C******************************************
```

```
02020C*   HORIZONTAL POLARIZATION   *
02030C******************************
02040 400  PSI = PSI + ENC
02050 IF (PSI .GT. 90.0) GO TO 640
02060 IF (PSI .LT. 10.1) GO TO 450
02070 PSI = PSI + ENC2
02080 450 PSIRAD = 0.01745329252*PSI
02090 SNPSI = SIN(PSIRAD)
02100 CNPSI = COS(PSIRAD)
02110 TSQ = CSQRT(Y-J*X-(CNPSI**2))
02120 RH = (SNPSI - TSQ)/(SNPSI + TSQ)
02130C*******************************************************************
02140C*  RH & RV ARE HORIZONTAL AND VERTICAL REFLECTION COEFFICIENTS *
02150C*******************************************************************
02160 E = TAN(BL/2.)*(CEXP(J*BH*SNPSI)+RH*CONJG(CEXP(J*BH*SNPSI)))
02170 E2 = 120.*CABS(E*E)/REAL(ZR)
02180C*******************************************************************
02190C*  THE GAIN EQUATION IS BASICALLY JORDAN'S EQN. 12-18 USING   *
02200C*   EFFECTIVE LENGTH = (2/BETA)*TAN(BL/2) FOR THE H-PLANE      *
02210C*   PATTERN OF A HORIZONTAL DIPOLE                            *
02220C*******************************************************************
02230 GAIN = 10.0*ALOG10(E2)
02240 500 FORMAT(2F15.3)
02250 PRINT 500,PSI,GAIN
02260 GO TO 400
02270 600 FORMAT(*PRESS RETURN FOR E-PLANE PATTERN OR TYPE CNTL T*)
02280 640 PRINT 600
02290 PAUSE
02300 650 FORMAT(*E-PLANE ELEVATION ANGLE IN DEGREES AND GAIN IN DB*)
02310 660 PRINT 650
02320 IF(POLAR.EQ.1.) PRINT 355
02330 IF(POLAR.EQ.0.) PRINT 356
02340 PSI = -ENC + 0.0001
02350C******************************
02360C*  VERTICAL POLARIZATION   *
02370C******************************
02380 700 PSI = PSI + ENC
02390 IF (PSI .GT. 90.0) GO TO 900
02400 IF (PSI .LT. 10.1) GO TO 800
02410 PSI = PSI + ENC2
02420 800 PSIRAD = 0.01745329252*PSI
02430 SNPSI = SIN(PSIRAD)
02440 CNPSI = COS(PSIRAD)
02450 TSQ = CSQRT(Y-J*X-(CNPSI**2))
02460 RV = (((Y-J*X)*SNPSI)-TSQ)/(((Y-J*X)*SNPSI)+TSQ)
02470 IF(POLAR.EQ.1.) GO TO 850
02480 E = (CEXP(J*BH*SNPSI)+RV*CONJG(CEXP(J*BH*SNPSI)))*(COS(BL)
02490+  -COS(BL*SNPSI))/(CNPSI*SIN(BL))
02500C*******************************************************************
02510C*  THE TERMS IN THE PREVIOUS LINE FOLLOWING THE SIXTH * ARE   *
02520C*  A GENERAL FORM OF THE EFFECTIVE LENGTH INCORPORATING       *
02530C*  ELEVATION ANGLE FOR A VERTICAL DIPOLE                     *
02540C*******************************************************************
02550 E2 = 120.*CABS(E*E)/REAL(ZR)
02560 IF(E2.EQ.0.) E2=1.E-12
02570 GAIN = 10.0*ALOG10(E2)
02580 PRINT 500,PSI,GAIN
02590 GO TO 700
02600C*******************************************************************
02610C*  VERTICAL POLARIZATION FOR A HORIZONTAL DIPOLE   *
02620C*******************************************************************
02630 850 E = (CEXP(J*BH*SNPSI)-RV*CONJG(CEXP(J*BH*SNPSI)))*(COS(BL)
02640+       -COS(BL*CNPSI))/(SNPSI*SIN(BL))
02650C*******************************************************************
```

```
02660C*   THE TERMS IN THE PREVIOUS LINE FOLLOWING THE SIXTH * ARE A   *
02670C*   GENERAL FORM OF THE EFFECTIVE LENGTH INCORPORATING ELEVATION *
02680C*   ANGLE FOR THE E-PLANE PATTERN OF A HORIZONTAL DIPOLE.        *
02690C********************************************************************
02700 E2 = 120.0*CABS(E*E)/REAL(ZR)
02710 GAIN = 10.0*ALOG10(E2)
02720 PRINT 500,PSI,GAIN
02730 GO TO 700
02740C********************************************************************
02750C*   CALCULATIONS END HERE.  USER MAY START OVER OR CONTINUE WITH *
02760C*   SAME DIPOLE ANTENNA GEOMETRY BUT A DIFFERENT HEIGHT, OR STOP *
02770C********************************************************************
02780 870 FORMAT(*- - - - - - - - - - - - - - - - - - - - - - - -*////)
02790 900 PRINT 870
02800 910 FORMAT(*ENTER DIPOLE HEIGHT IN METERS,*)
02810 920 FORMAT(*TYPE 0 TO START OVER, OR TYPE CNTL T*)
02820C********************************************************************
02830C*   NOTE:  CONTROL T IS THE BREAK MODE FOR THE CYBER 170/750 *
02840C*          OPERATING SYSTEM.                                 *
02850C********************************************************************
02860 IF(MOND.EQ.0.) PRINT 920
02870 IF(MOND.EQ.1.) PRINT 910
02880 IF(MOND.EQ.1.) PRINT 920
02890 READ 3,H
02900 IF(H.GT.0.) GO TO 12
02910 IF(H.EQ.0.) GO TO 1
02920 END
02930C********************************************************************
02940     SUBROUTINE MUTUAL(BETA,H,J,L,RH90,RV90,ZM,X,Y,POLAR,T)
02950C********************************************************************
02960 DIMENSION S(21),C(21),T(44),ARG(5),SI(5),CI(5)
02970 REAL L,L1,L2,L3,L4
02980 COMPLEX J,RH90,RV90,TSC,ZM
02990C********************************************************************
03000C*   COMPUTE REFLECTION COEFFICIENTS FOR PSI = 90 DEG   *
03010C********************************************************************
03020 RV90 = ((Y-J*X)-CSQRT(Y-J*X))/((Y-J*X)+CSQRT(Y-J*X))
03030 RH90 = (1.-CSQRT(Y-J*X))/(1.+CSQRT(Y-J*X))
03040 IF(X.EQ.0.) GO TO 30
03050C********************************************************************
03060C*   COMPUTE ARGUMENTS FOR SINE AND COSINE INTEGRALS   *
03070C********************************************************************
03080 YO = 0.
03090 XO = 2.*H
03100 IF(POLAR.EQ.0.) GO TO 1
03110 YO = 2.*H
03120 XO = 0.
03130C********************************************************************
03140C*   XO IS THE SEPARATION BETWEEN THE FEEDPOINTS OF THE VERTICAL   *
03150C*   DIPOLE AND ITS COLINEAR IMAGE.  YO IS THE SEPARATION BETWEEN  *
03160C*   THE HORIZONTAL DIPOLE AND ITS IMAGE.                          *
03170C********************************************************************
03180 1 B = BETA
03190 YO2 = YO**2
03200 HL1 = XO-2.*L
03210 HL2 = XO-L
03220 HL3 = XO
03230 HL4 = XO+L
03240 HL5 = XO+2.*L
03250 ARG(1) = B*(SQRT(YO2+HL1**2)+HL1)
03260 ARG(2) = B*(SQRT(YO2+HL2**2)+HL2)
03270 ARG(3) = B*(SQRT(YO2+HL3**2)+HL3)
03280 ARG(4) = B*(SQRT(YO2+HL4**2)+HL4)
03290 ARG(5) = B*(SQRT(YO2+HL5**2)+HL5)
```

```
03300 DO 9, I=1,5
03310 Z = ARG(I)
03320 IF(Z.GT.1.) GO TO 7
03330C************************************************************
03340C*  COMPUTE SI(ARG(I)) AND CI(ARG(I)) FOR 0<ARG(I)<1    *
03350C************************************************************
03360 DO 5 N=1,20
03370 5 S(N)=((-1)**N)*(Z**(2*N+1))/((2*N+1)*T(2*N+2))
03380 SI(I) = Z+S(1)+S(2)+S(3)+S(4)+S(5)+S(6)+S(7)+S(8)+S(9)+S(10)+S(11)
03390+         +S(12)+S(13)+S(14)+S(15)+S(16)+S(17)+S(18)+S(19)+S(20)
03400 DO 6 N=1,20
03410 6 C(N)=((-1)**N)*(Z**(2*N))/((2*N)*T(2*N+1))
03420 SA = C(1)+C(2)+C(3)+C(4)+C(5)+C(6)+C(7)+C(8)+C(9)+C(10)+C(11)
03430+       +C(12)+C(13)+C(14)+C(15)+C(16)+C(17)+C(18)+C(19)+C(20)
03440 CI(I) = 0.5772156665 + ALOG(Z) + SA
03450 GO TO 9
03460C************************************************************************
03470C*  COMPUTE SI(ARG(I)) AND CI(ARG(I)) FOR 1<ARG(I)<INFINITY    *
03480C************************************************************************
03490 7 FZ=(Z**8+38.027264*(Z**6)+265.187033*(Z**4)+335.67732*(Z**2)
03500+      +38.102495)/(Z*((Z**8)+40.021433*(Z**6)+322.62491)*(Z**4)
03510+      +570.23628*(Z**2)+157.105423))
03520 GZ = (Z**8+42.242855*(Z**6)+302.757865*(Z**4)+352.018498*(Z**2)
03530+      +21.821899)/((Z**2)*((Z**8)+48.196927*(Z**6)+482.485984
03540+      *(Z**4)+1114.978885*(Z**2)+449.690326))
03550 SI(I) = 1.570796327-FZ*COS(Z)-GZ*SIN(Z)
03560 CI(I) = FZ*SIN(Z)-GZ*COS(Z)
03570 9 CONTINUE
03580 IF(POLAR.EQ.0.) GO TO 15
03590C************************************************************************
03600C*  COMPUTE MUTUAL IMPEDANCE USING EQUATIONS FROM H.E. KING  *
03610C*  [5] FOR HORIZONTAL POLARIZATION                          *
03620C************************************************************************
03630 R12 = 30.*(COS(2.*B*L)*(CI(1)+CI(5)-2.*CI(2)-2.*CI(4)+2.*CI(3))
03640+           +SIN(2.*B*L)*(-SI(1)+SI(5)+2.*SI(2)-2.*SI(4))
03650+           +4.*CI(3)-2.*CI(2)-2.*CI(4))
03660 X12 = 30.*(COS(2.*B*L)*(-SI(1)-SI(5)+2.*SI(2)+2.*SI(4)-2.*SI(3))
03670+           +SIN(2.*B*L)*(-CI(1)+CI(5)+2.*CI(2)-2.*CI(4))
03680+           -4.*SI(3)+2.*SI(2)+2.*SI(4))
03690 ZM = R12+J*X12
03700 RETURN
03710C************************************************************************
03720C*  COMPUTE MUTUAL IMPEDANCE USING EQUATIONS FROM H.E. KING  *
03730C*  FOR VERTICAL POLARIZATION.                               *
03740C************************************************************************
03750 15 L1 = ALOG(HL2/HL1)
03760 L2 = ALOG(HL4/HL3)
03770 L3 = ALOG(HL2/HL3)
03780 L4 = ALOG(HL4/HL5)
03790 B1 = B*HL1
03800 B2 = B*HL3
03810 B3 = B*HL5
03820 B4 = B*HL2
03830 B5 = B*HL4
03840 R12=15.*(COS(B1)*(CI(1)-CI(2)+L1)+SIN(B1)*(SI(1)-SI(2))+COS(B2)
03850+    *(CI(3)-CI(4)+L2)+SIN(B2)*(SI(3)-SI(4))+COS(B2)*(-CI(2)+CI(3)
03860+    +L3)+SIN(B2)*(-SI(2)+SI(3))+COS(B3)*(-CI(4)+CI(5)+L4)+SIN(B3)
03870+    *(-SI(4)+SI(5))+2.*COS(B*L)*COS(B4)*(-CI(2)+CI(3)+L3)+2.
03880+    *COS(B*L)*SIN(B4)*(-SI(2)+SI(3))+2.*COS(B*L)*COS(B5)*(CI(3)
03890+    -CI(4)+L2)+2.*COS(B*L)*SIN(B5)*(SI(3)-SI(4)))
03900 X12=15.*(COS(B1)*(-SI(1)+SI(2))+SIN(B1)*(CI(1)-CI(2)-L1)+COS(B2)
03910+    *(-SI(3)+SI(4))+SIN(B2)*(CI(3)-CI(4)-L2)+COS(B2)*(SI(2)
03920+    -SI(3))+SIN(B2)*(-CI(2)+CI(3)-L3)+COS(B3)*(SI(4)-SI(5))
03930+    +SIN(B3)*(-CI(4)+CI(5)-L4)+2.*COS(B*L)*COS(B4)*(SI(2)
```

35

```
03940+      -SI(3))+2.*COS(B*L)*SIN(B4)*(-CI(2)+CI(3)-L3)+2.*COS(B*L)
03950+      *(-SI(3)+SI(4))+2.*COS(B*L)*SIN(B5)*(CI(3)-CI(4)-L2))
03960 ZM = F12+J*X12
03970 RETURN
03980 30 ZM = 0.0+J*0.0
03990 RETURN
04000 END
```

```
00100 PROGRAM ZMM1(INPUT,OUTPUT,TAPE1)
00110C*****************************************************************
00120C*    THIS PROGRAM CALCULATES SITE ATTENUATION BETWEEN A         *
00130C*    PARTICULAR SET OF HALF-WAVE DIPOLES POSITIONED OVER PLANE   *
00140C*    PERFECT GROUND.  THE OPEN CIRCUIT PROBE VOLTAGE IS OBTAINED*
00150C*    USING MUTUAL IMPEDANCES BETWEEN PROBE AND SOURCE ANTENNAS   *
00160C*    AND SOURCE ANTENNA IMAGES.  INPUT IMPEDANCES ARE CALCULATED*
00170C*    TAKING MUTUAL IMPEDANCES IN GROUND INTO ACCOUNT.            *
00180C*    THE INCIDENT POWER FROM A SIGNAL SOURCE IS 1 W WHICH        *
00190C*    IS USED WITH THE SOURCE DIPOLE INPUT IMPEDANCE, REFERRED TO*
00200C*    THE BASE, TO DETERMINE THE BASE CURRENT USED IN THE MUTUAL *
00210C*    IMPEDANCE CALCULATIONS.                                     *
00220C*    TAPE1 CONTAINS THE SITE ATTENUATION AMPLITUDE DATA.         *
00230C*    NOTES:                                                      *
00240C*         1. THE PROBE IS ASSUMED TO BE ATTACHED DIRECTLY TO A  *
00250C*            RECEIVER.  THAT IS, A LOSSLESS LINE IS ASSUMED.     *
00260C*         2. A LOSSLESS BALUN WITH A 1:1 TRANSFORMER RATIO IS    *
00270C*            ASSUMED.                                            *
00280C*         3. PROC. FILES D7 OR D7M ARE USED TO PLOT THE DATA.    *
00290C*         4. SAVE TAPES WITH REPLACE COMMAND AFTER RUN COMPLETE*
00300C*         5. IN THE DATA FILES: LEN IS DIPOLE HALF-LENGTH.       *
00310C*            RT IS THE RADIUS OF THE DIPOLE TIP IN METERS.       *
00320C*            RB IS THE RADIUS OF THE BASE OF THE DIPOLE, (AT     *
00330C*            THE FEEDPOINT).  RT = RB FOR A STRAIGHT ELEMENT.    *
00340C*            OBVIOUSLY, A LINEAR TAPER IS ASSUMED.               *
00350C*****************************************************************
00360 DIMENSION T(44),Z12(1000),Z1(1000),PREC(1000),VOC(1000),
00370+FREQ(10),LEN(10),RT(10),RB(10)
00380 REAL I1,L,LAMBDA,LEN
00390 COMPLEX J,Z12,Z1,ZP,ZR,ZS1
00400 DATA FREQ/30.,44.,65.,97.,143.,210.,311.,459.,677.,1000./
00410 DATA LEN/2.4,1.625,1.082,.717,.49,.331,.221,.147,.098,.0644/
00420 DATA RT/.0013,.0026,.0036,.005,.00235,.00235,.00235,.00235,
00430+.00235,.00235/
00440 DATA RB/.005,.005,.005,.005,.00235,.00235,.00235,.00235,.00235,
00450+.00235/
00460 10 FORMAT(F12.4)
00470 15 FORMAT(2F10.3)
00480 17 FORMAT(2I5)
00490 20 FORMAT(*INPUT DATA AFTER EACH ?*)
00500 PRINT 20
00510 30 FORMAT(*SOURCE DIPOLE FEEDPOINT HEIGHT OVER PERFECT GROUND, M*)
00520 PRINT 30
00530 READ 10,H2
00540 40 FORMAT(*PROBE DIPOLE NORMAL DISTANCE FROM SOURCE PLANE, M*)
00550 PRINT 40
00560 READ 10,RS
00570 IF(RS.LT.25.) HPSS=1.
00580 IF(RS.GT.25.) HPSS=2.
00590 IF(RS.LT.25.) HPF=4.
00600 IF(RS.GT.25.) HPF=6.
00610 HPI=0.01
00620C*****************************************************************
00630C*    THE ABOVE LINE SETS THE HEIGHT SCAN INCREMENT TO 0.01 M *
00640C*****************************************************************
00650 45 CONTINUE
00660 50 FORMAT(*TYPE 1. FOR HORIZONTAL POLARIZATION, 0 FOR VERTICAL*)
00670 PRINT 50
00680 READ 10,POLAR
00690C*****************************************************************
00700C*    RECEIVER AND TRANSMITTER IMPEDANCES ARE 100 OHMS   *
00710C*****************************************************************
00720 RECZ=100.
00730 TXZ =100.
```

```
00740 INC=0
00750 IF(POLAR.EQ.0) INC=1
00760C*****************************************************************
00770C*  INC IS ADJUSTED TO SKIP THE 30 MHZ DATA SET BECAUSE THE 30 MHZ *
00780C*  DIPOLE HALF-LENGTH EXCLUDES ITS USE VERTICALLY POLARIZED      *
00790C*****************************************************************
00800 60 INC=INC+1
00810 F=FREQ(INC)
00820 L=LEN(INC)
00830 RT=RT(INC)
00840 RB=RB(INC)
00850 HPS=HPSS
00860 IF(POLAR.EQ.0.AND.HPS.LE.L) HPS=L+0.05
00870 N=INT(0.0001+(HPF-HPS)/HPI)+1
00880 J=CMPLX(0.,1.)
00890 PI=3.14159265
00900 LAMBDA=299.792458/F
00910 BETA=2.*PI/LAMBDA
00920 K=1
00930 T(1)=1.
00940 DO 200 MM=1,42
00950 K=K+1
00960 200 T(K)=MM*T(K-1)
00970C*****************************************************************
00980C*  ALL INPUT AND MUTUAL IMPEDANCES ARE REFERRED TO THE      *
00990C*  BASE OR TERMINAL CURRENT.                                *
01000C*****************************************************************
01010 CALL IMPED(H2,BETA,J,L,LAMBDA,RT,RB,ZR,POLAR,T)
01020 ZS1=ZR
01030 CALL ZZ(BETA,HPS,HPF,HPI,H2,J,L,LAMBDA,RS,Z12,POLAR,T)
01040 DO 300 I=1,N
01050 300 Z1(I)=Z12(I)
01060 PINC = 1.0
01070 PTR=PINC*(1.-(CABS((ZS1-TXZ)/(ZS1+TXZ)))**2)
01080 I1=SQRT(PTR/REAL(ZS1))
01090 HP=HPS-HPI
01100 DO 500 I=1,N
01110 VOC(I)=CABS(I1*Z1(I))
01120 HP=HP+HPI
01130 CALL IMPED(HP,BETA,J,L,LAMBDA,RT,RB,ZR,POLAR,T)
01140 ZP=ZR
01150 500 PREC(I)=((VOC(I)/CABS(RECZ+ZP))**2)*RECZ
01160 PMAX=PREC(1)
01170 DO 600 I=2,N
01180 600 PMAX=AMAX1(PMAX,PREC(I))
01190 SMIN=10.*ALOG10(PINC/PMAX)
01200C*****************************************************************
01210C*  THE ABOVE 5 LINES OF CODE FIND THE MAXIMUM RECEIVED *
01220C*  POWER INTO A RECEIVER ATTACHED TO THE PROBE         *
01230C*  DIPOLE AND USE IT TO CALCULATE THE MINIMUM RELATIVE *
01240C*  INSERTION LOSS WHICH IS THE SITE ATTENUATION        *
01250C*****************************************************************
01260 WRITE(1,15)SMIN,F
01270 800 FORMAT(*EXECUTING!*)
01280 PRINT 800
01290 IF(FREQ(INC).LT.1000.) GO TO 60
01300 IF(POLAR.EQ.1.) GO TO 45
01310 END
01320C*****************************************************************
01330    SUBROUTINE IMPED(A,BETA,J,L,LAMBDA,RT,RB,ZR,POLAR,T)
01340C*  IS USED TO OBTAIN THE SELF IMPEDANCE OF THE SOURCE  *
01350C*  AND PROBE ANTENNAS USING SCHELKUNOFF'S EQUATIONS    *
01360C*  WE START BY COMPUTING THE SINE                      *
01370C*  AND COSINE INTEGRALS SI(M) AND CIN(M).  SUBROUTINE  *
```

```
01380C*   MUTUAL IS FINALLY CALLED TO ENABLE THE CALCULATION   *
01390C*   OF THE INPUT IMPEDANCE OVER GROUND.                   *
01400C***********************************************************
01410 DIMENSION SI(2),CIN(2),S(21),C(21),T(44),Z(2)
01420 REAL KA,L,LAMBDA,MBL
01430 COMPLEX CT,J,NBL,R,ZA,ZIND,ZINN,ZM,ZR,ZI
01440 BL = BETA*L
01450 B = 2.*BETA*L
01460 DO 60 M=1,2
01470 Z(M) = M*B
01480 DO 40 N = 1,20
01490 40 S(N) = ((-1)**N)*(Z(M)**(2*N+1))/((2*N+1)*T(2*N+2))
01500 SI(M)=Z(M)+S(1)+S(2)+S(3)+S(4)+S(5)+S(6)+S(7)+S(8)+S(9)+S(10)
01510+      +S(11)+S(12)+S(13)+S(14)+S(15)+S(16)+S(17)+S(18)+S(19)+S(20)
01520 DO 50 N = 1,20
01530 50 C(N) = ((-1)**N)*(Z(M)**(2*N))/((2*N)*T(2*N+1))
01540 60 CIN(M)=-(C(1)+C(2)+C(3)+C(4)+C(5)+C(6)+C(7)+C(8)+C(9)+C(10)
01550+     +C(11)+C(12)+C(13)+C(14)+C(15)+C(16)+C(17)+C(18)+C(19)+C(20))
01560C***********************************************************
01570C*   COMPUTE SELF IMPEDANCE, ZI, USING EQN 108 OF SCHELKUNOFF     *
01580C*   AND FRIIS.                                                   *
01590C***********************************************************
01600 IF(RT.EQ.RB) KA = 120.*(ALOG(2.*L/RT)-1.)
01610 IF(RT.NE.RB) KA=120.*(ALOG(2+L/RB)+(RT/(RB-RT))*ALOG(RT/RB))
01620 MBL = 60.*(CIN(1)-1.+COS(B))
01630 NBL = J*60.*(SI(1)-SIN(B))
01640 ZAR = 60.*CIN(1)+30.*(2.*CIN(1)-CIN(2))*COS(B)+30.*(SI(2)
01650+      -2.*SI(1))*SIN(B)
01660 ZAI = 60.*SI(1)-30.*(CIN(2)-ALOG(4.))*SIN(B)-30.*SI(2)*COS(B)
01670 ZA = ZAR+J*ZAI
01680 CT = J*RT/(30.*LAMBDA)
01690 ZINN = KA*((KA-MBL)*COS(BL)+J*(ZA+CT*KA*KA-NBL)*SIN(BL))
01700 ZIND = (ZA+CT*KA*KA+NBL)*COS(BL)+J*(KA+MBL)*SIN(BL)
01710 ZI = ZINN/ZIND
01720 IF(A.GT.0.066*LAMBDA) GO TO 70
01730 H1=0.0001*LAMBDA
01740 POL=1.
01750 CALL MUTUAL(BETA,H1,J,L,ZM,POL,T)
01760 ZI=ZM/(SIN(BL)**2)
01770 70 CONTINUE
01780C***********************************************************
01790C*   THE ABOVE 6 LINES HELP PREVENT NEGATIVE INPUT IMPEDANCES *
01800C*   FOR HORIZONTAL DIPOLES NEAR GROUND BECAUSE SCHELKUNOFF'S *
01810C*   INPUT IMPEDANCE DOES NOT CONVERGE TO THAT COMPUTED BY    *
01820C*   SUBROUTINE MUTUAL.                                       *
01830C***********************************************************
01840 CALL MUTUAL(BETA,A,J,L,ZM,POLAR,T)
01850 IF(POLAR.EQ.1.) ZR=ZI-ZM/((SIN(BL)**2))
01860 IF(POLAR.EQ.0.) ZR=ZI+ZM/((SIN(BL)**2))
01870 RETURN
01880 END
01890C***********************************************************
01900     SUBROUTINE MUTUAL(BETA,H,J,L,ZM,POLAR,T)
01910C*   USES EQUATIONS FROM H.E. KING,"MUTUAL IMPEDANCE OF       *
01920C*   UNEQUAL LENGTH ANTENNAS IN ECHELON", IRE TRANS. ANT.     *
01930C*   AND PROP., JULY 1957.                                    *
01940C***********************************************************
01950 DIMENSION S(21),C(21),T(44),ARG(5),SI(5),CI(5)
01960 REAL L,L1,L2,L3,L4
01970 COMPLEX J,ZM
01980C****-*****************************************************
01990C*   COMPUTE ARGUMENTS FOR SINE AND COSINE INTEGRALS  *
02000C***********************************************************
02010 YO = 0.
```

```
02020 X0 = 2.*H
02030 IF(POLAR.EQ.0.) GO TO 1
02040 Y0 = 2.*H
02050 X0 = 0.
02060C*******************************************************************
02070C*   X0 IS THE SEPARATION BETWEEN THE FEEDPOINTS OF THE VERTICAL  *
02080C*   DIPOLE AND ITS COLINEAR IMAGE.  Y0 IS THE SEPARATION BETWEEN *
02090C*   THE HORIZONTAL DIPOLE AND ITS IMAGE.                         *
02100C*******************************************************************
02110 1 B = BETA
02120 Y02 = Y0**2
02130 HL1 = X0-2.*L
02140 HL2 = X0-L
02150 HL3 = X0
02160 HL4 = X0+L
02170 HL5 = X0+2.*L
02180 ARG(1) = B*(SQRT(Y02+HL1**2)+HL1)
02190 ARG(2) = B*(SQRT(Y02+HL2**2)+HL2)
02200 ARG(3) = B*(SQRT(Y02+HL3**2)+HL3)
02210 ARG(4) = B*(SQRT(Y02+HL4**2)+HL4)
02220 ARG(5) = B*(SQRT(Y02+HL5**2)+HL5)
02230 DO 9, I=1,5
02240 Z = ARG(I)
02250 IF(Z.GT.1.) GO TO 7
02260C*******************************************************************
02270C*  COMPUTE SI(ARG(I)) AND CI(ARG(I)) FOR 0<ARG(I)<1   *
02280C*******************************************************************
02290 DO 5 N=1,20
02300 5 S(N)=((-1)**N)*(Z**(2*N+1))/((2*N+1)*T(2*N+2))
02310 SI(I) = Z+S(1)+S(2)+S(3)+S(4)+S(5)+S(6)+S(7)+S(8)+S(9)+S(10)+S(11)
02320+        +S(12)+S(13)+S(14)+S(15)+S(16)+S(17)+S(18)+S(19)+S(20)
02330 DO 6 N=1,20
02340 6 C(N)=((-1)**N)*(Z**(2*N))/((2*N)*T(2*N+1))
02350 SA = C(1)+C(2)+C(3)+C(4)+C(5)+C(6)+C(7)+C(8)+C(9)+C(10)+C(11)
02360+      +C(12)+C(13)+C(14)+C(15)+C(16)+C(17)+C(18)+C(19)+C(20)
02370 CI(I) = 0.577215665 + ALOG(Z) + SA
02380 GO TO 9
02390C*******************************************************************
02400C*  COMPUTE SI(ARG(I)) AND CI(ARG(I)) FOR 1<ARG(I)<INFINITY  *
02410C*******************************************************************
02420 7 FZ=(Z**8+38.027264*(Z**6)+265.187033*(Z**4)+335.67732*(Z**2)
02430+      +38.102495)/(Z*((Z**8)+40.021433*(Z**6)+322.624911*(Z**4)
02440+      +(Z**2)+570.23628*(Z**2)+157.105423))
02450 GZ = (Z**8+42.242855*(Z**6)+302.757865*(Z**4)+352.018498*(Z**2)
02460+      +21.821899)/((Z**2)*((Z**8)+46.196927*(Z**6)+482.485984
02470+      *(Z**4)+1114.978885*(Z**2)+449.690326))
02480 SI(I) = 1.570796327-FZ*COS(Z)-GZ*SIN(Z)
02490 CI(I) = FZ*SIN(Z)-GZ*COS(Z)
02500 9 CONTINUE
02510 IF(POLAR.EQ.0.) GO TO 15
02520C*******************************************************************
02530C*  COMPUTE MUTUAL IMPEDANCE USING EQUATIONS FROM H.E. KING  *
02540C*   FOR HORIZONTAL POLARIZATION                            *
02550C*******************************************************************
02560 R12= 30.*(COS(2.*B*L)*(CI(1)+CI(5)-2.*CI(2)-2.*CI(4)+2.*CI(3))
02570+          +SIN(2.*B*L)*(-SI(1)+SI(5)+2.*SI(2)-2.*SI(4))
02580+          +4.*CI(3)-2.*CI(2)-2.*CI(4))
02590 X12 = 30.*(COS(2.*B*L)*(-SI(1)-SI(5)+2.*SI(2)+2.*SI(4)-2.*SI(3))
02600+          +SIN(2.*B*L)*(-CI(1)+CI(5)+2.*CI(2)-2.*CI(4))
02610+          -4.*SI(3)+2.*SI(2)+2.*SI(4))
02620 ZM = R12+J*X12
02630 RETURN
02640C*******************************************************************
02650C*  COMPUTE MUTUAL IMPEDANCE USING EQUATIONS FROM H.E. KING  *
```

```
02660C*   FOR VERTICAL POLARIZATION                                          *
02670C***************************************************************
02680 15 L1 = ALOG(HL2/HL1)
02690 L2 = ALOG(HL4/HL3)
02700 L3 = ALOG(HL2/HL3)
02710 L4 = ALOG(HL4/HL5)
02720 B1 = B*HL1
02730 B2 = B*HL3
02740 B3 = B*HL5
02750 B4 = B*HL2
02760 B5 = B*HL4
02770 R12=15.*(COS(B1)*(CI(1)-CI(2)+L1)+SIN(B1)*(SI(1)-SI(2))+COS(B2)
02780+     *(CI(3)-CI(4)+L2)+SIN(B2)*(SI(3)-SI(4))+COS(B2)*(-CI(2)+CI(3)
02790+     +L3)+SIN(B2)*(-SI(2)+SI(3))+COS(B3)*(-CI(4)+CI(5)+L4)+SIN(B3)
02800+     *(-SI(4)+SI(5))+2.*COS(B*L)*COS(B4)*(-CI(2)+CI(3)+L3)+2.
02810+     *COS(B*L)*SIN(B4)*(-SI(2)+SI(3))+2.*COS(B*L)*COS(B5)*(CI(3)
02820+     -CI(4)+L2)+2.*COS(B*L)*SIN(B5)*(SI(3)-SI(4)))
02830 X12 = 15.*(COS(B1)*(-SI(1)+SI(2))+SIN(B1)*(CI(1)-CI(2)-L1)+COS(B2)
02840+     *(-SI(3)+SI(4))+SIN(B2)*(CI(3)-CI(4)-L2)+COS(B2)*(SI(2)
02850+     -SI(3))+SIN(B2)*(-CI(2)+CI(3)-L3)+COS(B3)*(SI(4)-SI(5))
02860+     +SIN(B3)*(-CI(4)+CI(5)-L4)+2.*COS(B*L)*COS(B4)*(SI(2)
02870+     -SI(3))+2.*COS(B*L)*SIN(B4)*(-CI(2)+CI(3)-L3)+2.*COS(B*L)
02880+     *(-SI(3)+SI(4))+2.*COS(B*L)*SIN(B5)*(CI(3)-CI(4)-L2))
02890 ZM = R12+J*X12
02900 RETURN
02910 END
02920C***************************************************************
02930     SUBROUTINE ZZ(BETA,HPS,HPF,HPI,HS,J,L,LAMBDA,RS,Z12B,POLAR,T)
02940C*   COMPUTES THE MUTUAL IMPEDANCE BETWEEN EACH SOURCE AND SOURCE  *
02950C*   IMAGE AND THE PROBE ANTENNA.  M=0 FOR THE PROBE AND ONE SOURCE *
02960C*   CALCULATION AND M=1 FOR THE PROBE TO IMAGE CALCULATIONS.       *
02970C***************************************************************
02980 DIMENSION ARG(18),S(21),C(21),T(44),SI(18),CI(18),R12(1000),
02990+X12(1000),Z12L(1000),Z12B(1000),SIS(18),SIL(18),CIS(18),CIL(18)
03000 REAL LAMBDA,L
03010 COMPLEX J,Z12L,Z12B
03020 B=BETA
03030 M=0
03040 10 HP=HPS-HPI
03050 K=0
03060 20 HP=HP+HPI
03070 K=K+1
03080 IF(POLAR.EQ.0.) D=RS
03090 IF(POLAR.EQ.1.AND.M.EQ.0.) D=SQRT(RS*RS+(HS-HP)**2)
03100 IF(POLAR.EQ.1.AND.M.EQ.1.) D=SQRT(RS*RS+(HS+HP)**2)
03110 IF(POLAR.EQ.0.AND.M.EQ.0.) H=HS-HP-L
03120 IF(POLAR.EQ.1.) H=-L
03130 IF(POLAR.EQ.0.AND.M.EQ.1.) H=HS+HP-L
03140 ARG(1)=B*(SQRT(D*D+(H-L)**2)+(H-L))
03150 ARG(2)=B*(SQRT(D*D+(H-L)**2)-(H-L))
03160 ARG(3)=B*(SQRT(D*D+(H+L)**2)-(H+L))
03170 ARG(4)=B*(SQRT(D*D+(H+L)**2)+(H+L))
03180 ARG(5)=B*(SQRT(D*D+(H)**2)+(H))
03190 ARG(6)=B*(SQRT(D*D+(H)**2)-(H))
03200 ARG(7)=B*(SQRT(D*D+(H+2*L)**2)-(H+2*L))
03210 ARG(8)=B*(SQRT(D*D+(H+2*L)**2)+(H+2*L))
03220 ARG(9)=B*(SQRT(D*D+(H+L)**2)+(H+L))
03230 ARG(10)=B*(SQRT(D*D+(H+L)**2)-(H+L))
03240 ARG(11)=B*(SQRT(D*D+(H+3*L)**2)-(H+3*L))
03250 ARG(12)=B*(SQRT(D*D+(H+3*L)**2)+(H+3*L))
03260 ARG(13)=B*(SQRT(D*D+H*H)-H)
03270 ARG(14)=B*(SQRT(D*D+H*H)+H)
03280 ARG(15)=B*(SQRT(D*D+(H+L)**2)-(H+L))
03290 ARG(16)=B*(SQRT(D*D+(H+L)**2)+(H+L))
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03300 ARG(17)=B*(SQRT(D*D+(H+2.*L)**2)-(H+2.*L))
03310 ARG(18)=B*(SQRT(D*D+(H+2.*L)**2)+(H+2.*L))
03320 DO 100,I=1,18
03330 Z=ARG(I)
03340 IF(Z.GT.2.) GO TO 70
03350C*********************************************************
03360C*  COMPUTE SI(ARG(I)) AND CI(ARG(I)) FOR 0<ARG(I)<1  *
03370C*********************************************************
03380 DO 50 N=1,20
03390 50 S(N)=((-1)**N)*(Z**(2*N+1))/((2*N+1)*T(2*N+2))
03400 SIS(I) = Z+S(1)+S(2)+S(3)+S(4)+S(5)+S(6)+S(7)+S(8)+S(9)+S(10)+S(11)
03410+        +S(12)+S(13)+S(14)+S(15)+S(16)+S(17)+S(18)+S(19)+S(20)
03420 DO 60 N=1,20
03430 60 C(N)=((-1)**N)*(Z**(2*N))/((2*N)*T(2*N+1))
03440 SA = C(1)+C(2)+C(3)+C(4)+C(5)+C(6)+C(7)+C(8)+C(9)+C(10)+C(11)
03450+      +C(12)+C(13)+C(14)+C(15)+C(16)+C(17)+C(18)+C(19)+C(20)
03460 CIS(I) = 0.577215665 + ALOG(Z) + SA
03470C*********************************************************
03480C*  COMPUTE SI(ARG(I)) AND CI(ARG(I)) FOR 1<ARG(I)<INFINITY  *
03490C*********************************************************
03500 IF(Z.LE.1.) GO TO 80
03510 70 FZ=(Z**8+38.027264*(Z**6)+265.187033*(Z**4)+335.67732*(Z**2)
03520+      +38.102495)/(Z*((Z**8)+40.021433*(Z**6)+322.624911*(Z**4)
03530+      +570.23628*(Z**2)+157.105423))
03540 GZ = (Z**8+42.242855*(Z**6)+302.757865*(Z**4)+352.018498*(Z**2)
03550+      +21.821899)/((Z**2)*((Z**8)+48.196927*(Z**6)+482.485984
03560+      *(Z**4)+1114.978885*(Z**2)+449.690326))
03570 SIL(I) = 1.570796327-FZ*COS(Z)-GZ*SIN(Z)
03580 CIL(I)=FZ*SIN(Z)-GZ*COS(Z)
03590C*********************************************************
03600C*  THE FOLLOWING SIX LINES ARE AN INTERPOLATION ROUTINE TO  *
03610C*  SMOOTH THE TRANSITION REGION BETWEEN THE LARGE AND SMALL  *
03620C*  ARGUMENT APPROXIMATIONS TO THE SINE AND COSINE INTEGRALS  *
03630C*********************************************************
03640 80 IF(Z.LE.1.) SI(I)=SIS(I)
03650 IF(Z.LE.1.) CI(I)=CIS(I)
03660 IF(Z.GT.1.AND.Z.LE.2.) SI(I)=SIS(I)+(Z-1.)*(SIL(I)-SIS(I))
03670 IF(Z.GT.1.AND.Z.LE.2.) CI(I)=CIS(I)+(Z-1.)*(CIL(I)-CIS(I))
03680 IF(Z.GT.2.) SI(I)=SIL(I)
03690 IF(Z.GT.2.) CI(I)=CIL(I)
03700 100 CONTINUE
03710C*********************************************************
03720C*  COMPUTE MUTUAL IMPEDANCE USING EQUATIONS FROM H.E. KING  *
03730C*********************************************************
03740 R12(K)=15.*(COS(B*(L-H))*(CI(1)+CI(2)-CI(5)-CI(6))+SIN(B*(L-H))
03750+*(-SI(1)+SI(2)+SI(5)-SI(6))+COS(B*(L+H))*(CI(3)+CI(4)-CI(7)-CI(8))
03760++SIN(B*(L+H))*(-SI(3)+SI(4)+SI(7)-SI(8))+COS(B*(L-2.*L-H))*
03770+(-CI(5)-CI(6)+CI(9)+CI(10))+SIN(B*(L-2.*L-H))*(SI(5)-SI(6)-SI(9)
03780++SI(10))+COS(B*(L+2.*L+H))*(-CI(7)-CI(8)+CI(11)+CI(12))+SIN(B*
03790+(L+2.*L+H))*(SI(7)-SI(8)-SI(11)+SI(12))+2.*COS(B*L)*COS(B*H)*
03800+(-CI(13)-CI(14)+CI(15)+CI(16))+2.*COS(B*L)*SIN(B*H)*(SI(13)-SI(14)
03810+-SI(15)+SI(16))+2.*COS(B*L)*COS(B*(2.*L+H))*(CI(15)+CI(16)-CI(17)
03820+-CI(18))+2.*COS(B*L)*SIN(B*(2.*L+H))*(-SI(15)+SI(16)+SI(17)
03830+-SI(18)))
03840 X12(K)=15.*(COS(B*(L-H))*(-SI(1)-SI(2)+SI(5)+SI(6))+SIN(B*(L-H))
03850+*(-CI(1)+CI(2)+CI(5)-CI(6))+COS(B*(L+H))*(-SI(3)-SI(4)+SI(7)+SI(8))
03860++SIN(B*(L+H))*(-CI(3)+CI(4)+CI(7)-CI(8))+COS(B*(L-2.*L-H))*
03870+(+SI(5)+SI(6)-SI(9)-SI(10))+SIN(B*(L-2.*L-H))*(CI(5)-CI(6)-CI(9)
03880++CI(10))+COS(B*(L+2.*L+H))*(+SI(7)+SI(8)-SI(11)-SI(12))+SIN(B*
03890+(L+2.*L+H))*(CI(7)-CI(8)-CI(11)+CI(12))+2.*COS(B*L)*COS(B*H)*
03900+(+SI(13)+SI(14)-SI(15)-SI(16))+2.*COS(B*L)*SIN(B*H)*(CI(13)-CI(14)
03910+-CI(15)+CI(16))+2.*COS(B*L)*COS(B*(2.*L+H))*(-SI(15)-SI(16)+SI(17)
03920++SI(18))+2.*COS(B*L)*SIN(B*(2.*L+H))*(-CI(15)+CI(16)+CI(17)
03930+-CI(18)))
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03940 IF(POLAR.EQ.0.AND.M.EQ.1) Z12L(K)=Z12L(K)+R12(K)+J*X12(K)
03950 IF(POLAR.EQ.1.AND.M.EQ.1) Z12L(K)=Z12L(K)-R12(K)-J*X12(K)
03960 IF(M.EQ.0) Z12L(K)=R12(K)+J*X12(K)
03970 Z12B(K)=Z12L(K)/((SIN(BETA*L))**2)
03980C**********************************************************************
03990C*   THE TERMS IN THE PRECEEDING LINE FOLLOWING THE / CHANGE THE   *
04000C*   MUTUAL IMPEDANCE REFERENCE FROM THE LOOP CURRENT TO THE BASE  *
04010C*   CURRENT.  SEE JORDAN PP. 345-351.                             *
04020C**********************************************************************
04030 IF(HP.LT.HPF) GOTO 20
04040 M=M+1
04050 IF(M.LE.1) GOTO 10
04060 RETURN
04070 END
```

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

Site attenuation is a measure of performance of an open test site used at frequencies below about 1 GHz for antenna calibration and equipment emission and susceptibility testing. These sites typically consist of a large, obstruction-free ground plane and the hemisphere above it. Site attenuation of an ideal site is calculated and compared to data measured using the 30 m by 60 m NBS ground screen.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

antenna measurements; dipole antennas; site attenuation

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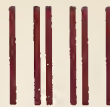*Order the following NBS publications—FIPS and NBSIR's—from the National Technical Information Service, Springfield, VA 22161.*

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